Matter & Radiation

WITH PARTICULAR REFERENCE TO THE DETECTION & USES OF THE INFRA-RED RAYS

BY

JOHN BUCKINGHAM, M.A.

Late Open Exhibitioner in Natural Science of St. John's College, Cambridge; Assistant Director of Scientific Research, Admiralty, S.W. 1

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Robert E. Tozier

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And every lord or lady what ye be
Or clerk that liketh for to rede this,
Besekyng lawly with humylite
Support where I have seyde amys;
Correcteth only there that nedful is,
If word or sentence be noght as it scholde.
My-self I am unsuffishaunt I-wys
For if I couthe have bettre done I wolde.

—BOETHIUS: *De Consolatione Philosophiæ*.
[John Walton's Translation. Early English Text Society, O.S. 170.]

Ignis ubique latet, naturam amplectitur omnem,
Cuncta parit, renovat, dividit, unit, alit.

—VOLTAIRE.

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PREFACE

IN this small book I have endeavoured to set down an outline of the theory of radiation, and, particularly, of the properties and uses of that group of invisible rays which are known as the Infra-Red. In order that the non-scientific reader may be relieved from an initial overload of strange words, which are a hindrance rather than an aid in acquiring a grasp of a new subject, I have avoided, so far as is possible, the use of terms which are not a part of the vocabulary of everyday life.

Even if the language is simple it does not follow that the book is easy reading, or that the ideas, which are essential to an understanding of the subject, are to be casually acquired. But the title of the book does not suggest light literature and is less likely, therefore, to be read by those who are unwilling to accept their share of the task which I have begun.

The subject has been a field for speculation from the earliest days, and there is no sign that a comprehensive explanation of the diverse effects of radiation is even now within sight. In fact, the discoveries of recent years have put into our hands definite evidence that the 'classical' theory is at fault, and must either be modified before it can embrace all existing knowledge, or it must be discarded and replaced by a fresh set of conceptions.

There is no need for any reader to feel surprised that scientists can willingly face the possible destruction of a theory which has in the past been regarded as most certainly true. Heinrich Hertz, the pioneer of modern Wireless Telegraphy, in 1889, when dealing with the nature of light, pointed out that so wonderful was the agreement between theory and experiment that 'a refutation of these

(classical) views is inconceivable to the physicist. The wave theory of light is, from the point of view of human beings, certainty.' And yet, after only forty years, we have evidence which appears to be in absolute conflict with the theory of which Hertz was so sure.

It may not be out of place here to make a few remarks about scientific theories and their place in our speculations. All our knowledge of the external world is admitted to our minds by the five senses. These are imperfect, for they can convey to the brain but a small fraction of all possible sensations. They are also imperfect because it is obvious that they misrepresent much of the impressions which they succeed in conveying—or, as Petronius says, 'Our eyes deceive us and our wandering senses weigh down our reason and tell us falsehoods. For the tower which stands almost four-square has its corners blunted at a distance and becomes rounded.' However, with these senses, we collect what pass for facts about our surroundings, and, when we have enough of these, we endeavour to make some mental image which will provide an explanation of our observations. This mental picture is a theory. The greater the number of observations which agree with deductions from our theory, the better are we pleased, and the more confidence do we place in the correctness of our mental picture. A theory must not be regarded as a final and true description of the causes of our sensations, but only as a convenient handbag in which we can stow away the results of many observations which would otherwise be left lying about in confusion. Theories are properly to be regarded as indispensable sign-posts in what would otherwise be a dark forest of 'facts'. These sign-posts are set up, not only in the explored areas of the forest, but also on the verges of the unexplored, so that they point the road to

unknown regions, which could not be entered by blundering unguided pioneers.

If we had been given infinite powers of perception and understanding the need of scientific theories would never have existed. As things are, however, there are many things in ordinary life which transcend the powers we have, and it is the business of scientists to explain, or try to explain, these things in terms of our actual perceptions, or of abstractions from them. These are the only materials which are given him to work with, and he must work with them or nothing. The scientist is happy if he can bring some sort of order into the chaos of perceptual impressions by using an easily visualized mental picture which says, in effect, 'Such and such behaves as if this and that were there, doing thus and thus'—'such and such' being things outside our ordinary direct knowledge, while 'this and that' and their doings 'thus and thus', are the idealized embodiments of common perceptions.

Since it is possible that all the imperfect information which the senses pass to the understanding is moulded or transformed in a particular manner by an activity of the understanding itself, we must always remember that scientific theories can, at best, be nothing more than a formal scheme representing an aspect of absolute truths. Therefore when, in what follows, I make statements concerning things which are outside our perception, it must be understood that these statements depend, for their truth, upon the accuracy of the fundamental theory or mental picture from which the statements follow. The justification for making any statements at all, on the basis of the theories outlined in this book, lies in the fact that a host of deductions which have been made from them are in accordance with everyday experience.

The writer of a book of this kind is liable to criticism on many grounds, and there are always people who will argue that one might as usefully try to convey the delicate charm of a Corot in a black-and-white print, as to give in simple prose any fair impression of the austere beauty of the mathematical and other conceptions which have been so fruitful in adding to our knowledge of the world of sensation in which we live. The argument is unanswerable, but, so long as there are any who ask for an impression, it seems to me that one is justified in endeavouring to give it.

I feel some regret that the contents of Chapter V show that the proposed applications of infra-red rays are mainly military, and I wish to make it clear that none of the information in this chapter has been drawn from official sources. The views expressed are my personal views and bear no necessary relation to any which may be held officially.

I wish to express my indebtedness to the Admiralty for giving me permission to write this book; to Mr. C. S. Wright, with whom I have happily been able to discuss the modern theories of radiation and the electrical structure of matter; to the Royal Society, for allowing me to use their Library; to those who have kindly permitted the reproduction of photographs and diagrams; and to those who have been good enough to assist in other ways.

J. B.

LONDON, S.W. I,
October 1929.

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Early Ideas about Light

A STUDY of literature teaches that men, women, and things are still much the same as they were in the days of the earliest writers. An astonishing change has, however, taken place in our outlook upon our surroundings. We have long been dissatisfied with the ancient habit of ascribing the goings on around us to the whims of deities of greater or less power, and we are living at a time when the tendency is to reduce all phenomena to questions of mechanics, i.e. to the actions of different sets of forces upon each other and upon ourselves and our surroundings.

The intimate connexion between the Sun and life on the earth is a reason for the prominence of Sun-gods in mythology. It is on record that the King Amenophis IV, who reigned in Egypt from about 1380 to 1362 B.C., proposed to supplant all the existing deities by a single god—'the great living disk of the Sun'. Not only does the Sun 'strengthen the eyes with his beams', but it is he 'who bringeth the years, createth the months, maketh the days and calculateth the hours, the lord of time, by whom men reckon.'[1] These and many other influences of the Sun were realized, but the spirit of inquiry was not awake and no coherent picture of the manner in which a so distant body could affect the earth was presented until the end of the seventeenth century.

There are certain obvious things about the radiation

which comes from the Sun and is called light. The formation of shadows which are geometrically similar to the objects causing them is a reason for suggesting that, whatever light may be, it is something which travels in straight lines, and, further, that this something is unable to travel through those objects which cast shadows. On the other hand, light is perfectly able to pass through a glass-sided vessel from which all the air has been pumped and this without any apparent diminution in its intensity. If we endeavour to explain how it is that any 'influence' can travel through a space where nothing is we are led to the conclusion that light might be a number of very small moving particles capable of affecting our eyes. These particles might be shot out of luminous bodies and would be able to penetrate some substances while they are stopped by others. Alternatively we might account for some of the properties of light by what is known as the emission theory, in which the surface of the eye was supposed to send out feelers which transmitted sensations from the object to the eye. This idea was dismissed by Leonardo da Vinci in these words:

> 'It is impossible that the eye should project from itself, by visual rays, the visual virtue, since, as soon as it opens, that front portion of the eye which would give rise to this emanation would have to go forth to the object, and this it could not do without time. And this being so, it could not travel so high as the Sun in a month's time when the eye wanted to see it . . . and if this virtue would have to travel through the air as perfumes do, the winds would bend it and carry it into another place.' [2]

With a further stretch of the imagination we might suggest that light is a kind of movement or disturbance travelling in a continuous fluid-like medium which cannot be removed from vessels by such crude things as

pumps, and must have properties very different from those of any ordinary substance.

Necessity of assuming a Medium to carry Light

If we analyse the mental processes by which we come to these possible pictures, we find that we are trying to dodge the difficulty of explaining how an influence of any kind can travel without something to carry it. Newton[3] was in the same trouble and was in no two minds about the necessity of assuming something which would account for 'action at a distance', for he said 'that one body can act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it'.

Admitting then that, since 'action at a distance' is inconceivable to us unless there is a medium to transmit the action, a medium therefore exists, we are led to inquire whether all 'actions' which travel take time to pass from one place to another. The ordinary disturbances of everyday life, such as noises and street vibrations, start from something which is in motion and take definite times to reach out over a distance. Those disturbances are passed on by the action of contiguous particles of materials upon each other. The particles of air which transmit to each other, and eventually to the ear, the movements of the body causing the sound, move just as the materials of a motor-bus which transmit the vibrations of a badly balanced engine to the occupants. When we feel this vibration we have no difficulty in realizing where it comes from or how it reaches us.

If it were shown that light also takes time to travel we should have made an advance because this discovery would bring light into line with other experiences which (like vibration) are easier to think about and understand.

Light takes Time to Travel from Place to Place

We remained in ignorance of the fact that light travels at a fixed rate until 1675, when Römer[4] observed what appeared to be an irregularity in the movements of the satellites of Jupiter. These satellites are eclipsed periodically by Jupiter, and one would naturally expect that, planets and satellites being creatures of regular habits, the eclipses would appear at regular intervals. Römer, on the contrary, noticed that the measured times between successive eclipses were longer when the earth was retreating from Jupiter and shorter when it was approaching. He explained this by assuming that the light from the satellites took a definite time to reach him, the apparent longer or shorter intervals being due to the increase or decrease in the distance between the earth and the planet during the intervals. From his observations Römer calculated the speed of light and his value was wrong by a matter of 6,000 miles per second. This sounds large, but when one remembers that the true velocity is about 186,000 miles per second, it will be seen that the disagreement is remarkably small for a first shot. Since Römer's time the speed of light has been measured and checked by numerous scientists not only by astronomical methods but also with complicated apparatus by which measurements of this great speed can be made over distances on the earth. The speed of light in many different transparent substances has also been measured and

it is generally found to be smaller than in space (or in a perfect vacuum), but it is always vastly greater than the speeds of any other disturbances to which we are normally accustomed.

Distinctions between Sound and Light

The speed of sound in air is roughly 1/5 of a mile per second, in water 1 mile, and in steel 3 miles. In explosives the speed with which the mass detonates when once set off may be 5 miles per second. All these speeds are minute compared with that of light and we account for the difference by saying that sounds travel in things which we can always feel and often see, while light travels by the aid of something no one has ever been able to detect with his senses and whose very existence is a strain upon the imagination. Sounds, unlike light, will not travel in a vacuum, and although an electric bell may be seen ringing in an empty glass jar, no sound whatever comes from it.

It is important to realize that sounds are always associated with movements of material particles and that almost any material is capable of transmitting sound to some extent. We are apt to lose sight of this fact because the sounds of everyday life come to us through the air and we forget—although it has been known for a very long time—that the human voice is well transmitted by water, steel, and other substances. Francis Bacon describes[5] an experiment in which a man descends under water with an inverted bucket over his head so that his mouth and nose are kept free from water. 'Then let him speak; and any that shall stand without shall hear his voice plainly; but yet made extreme sharp and exile, like the voice of puppets: but yet the articulate sounds of the words will not be confounded.'

The Chosen Path of Light

So far we have noticed nothing about light which could not be accounted for by the assumption of disturbances in an exceedingly tenuous medium or by the 'small particle' or corpuscular theory, and we have no real ground for

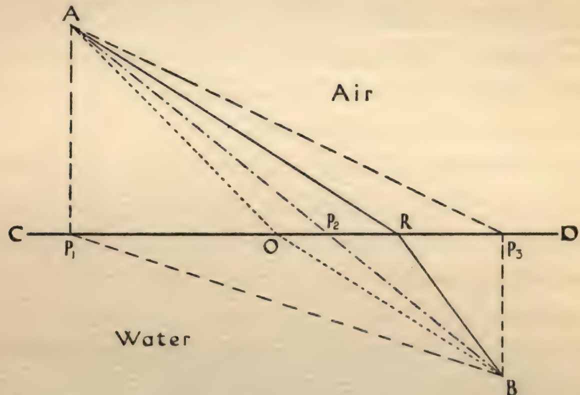

Fig. 1. The chosen path of Light

preferring either suggestion. It has been stated that light travels in straight lines, and this is true in open space or where the material through which it shines (say air or glass) is uniform in all directions. If light travelling in air comes upon a different substance, say water, the rays do not go straight across the boundary but are bent there. The apparent distortion of a straight stick poked into a stream is accounted for in this way. Since the path of the light is no longer straight it is natural to wonder if any particular path is chosen in preference to another. This point may be made clearer by reference to a diagram (Fig. 1).

Suppose a ray of light travels from the point *A* (in air) to the point *B* (in water), and that the water surface is represented by the line *CD*. The light might choose any

course such as the dotted line AOB, and as extreme cases it might travel along AP_1B or AP_3B, which correspond to a preference for getting as quickly as possible into the water or for going on as far as possible in the air. The straight course AP_2B is never taken. In point of fact one, and only one, course for the light is possible, and this, oddly enough, is the course which makes the *time* taken from A to B less than by any other way. Since the velocity of light is greater in air than it is in water, time will be saved if the greater portion of the journey is done in air, but the saving is not large enough to justify the extreme course AP_3B because of the undue total length of the journey. The straight journey AP_2B will take longer than some course such as ARB and the actual position of R can be calculated when the velocities of light in air and water are known. As an analogy we might suppose A is in a grass field and B is a scarecrow in the middle of a ploughed field, and that a man who can walk twice as fast on grass as he can over plough wishes to go from A to the scarecrow. He certainly will not try the tracks AP_1B or AP_3B but, if he is wise, will take some course lying between AP_2B and AP_3B, just as light does. It is interesting that the mathematical theory which leads to this result is obeyed however many surfaces the light may fall upon, or go through, on its trip. The result is the same—light always goes from point to point by the quickest path and never loses even the smallest fraction of a second anywhere. Light which is *reflected* from any surface whatever also obeys the regulation that it must go by the quickest route. Rays going from a source of light to a reflecting surface and those which come away from it are equally inclined to the surface because any other course would involve a waste of time. 'Oh! Marvellous, O Stupendous Necessity—by

thy laws thou dost compel every effect to be the direct result of its cause, by the shortest path. These indeed are miracles.'[6]

Difficulty of the Corpuscular Theory

The exponents of the corpuscular theory explained the bending of light by suggesting that the water had an attraction for the corpuscles and sucked them in as they arrived at the surface. The speed of the corpuscles was, they argued, greater in the water than in the air above it and light should therefore take a course such as *AOB*. This is the reverse of what is observed and the discovery was a blow to the dealers in corpuscles, but there was worse in store for them.

In 1801 Thomas Young[7] showed how it was possible to add light to light and produce—*darkness*. About a century and a half before this it had been shown experimentally that light appeared under some conditions to annihilate itself, but Young was the first to give a reasoned account of the way in which this could come about.

Like all good 'mechanical philosophers' Young argued mainly from the known properties of vibrations in material substances, and he had, in the previous year, read a paper in which he dwelt upon a number of similarities between sound (mechanical vibrations) and light. In so doing he was following a trail which had been laid by Huygens[8] in a book published in 1690, from which the following quotation is taken:

'De plus quand on considere l'extreme vitesse dont la lumiere s'étend de toutes parts, & que quand il en vient de differents endroits, mesme de tout opposez, elles se traversent l'une l'autre sans s'empescher; on comprend bien que quand nous voyons un objet lumineux, ce ne sauroit estre par le transport d'une matiere, qui depuis cet objet s'en vient jusqu'à nous, ainsi qu'une bale ou une fleche tra-

verse l'air: car assurément cela repugne trop à ces deux qualités de la lumiere, & sur tout la derniere. C'est donc d'une autre maniere qu'elle s'étend, & ce qui nous peut conduire à la comprendre c'est la connoissance que nous avons de l'extension du Son dans l'air.' [9]

In one of Young's experiments light went through a slit in a screen and then fell on a second in which were two small holes, close together. Two illuminated patches were then produced on a third screen and where these patches of light which had passed through the two holes overlapped, a series of bright and dark bands was seen. These bands disappeared if either of the holes was stopped. It is noteworthy that no light is actually lost. The appearance of dark bands is balanced by an increased brightness of the illumination in the bright bands.

It is not entirely impossible to account for this by straining the corpuscular theory but it is easily explained by what is now called the wave theory, which was advocated by Huygens. We can begin to see how blackness can come from the addition of two separate light disturbances in the following way. Suppose in the first place light is, as we know it is, an influence which travels. Then if we can imagine an influence which can have opposite qualities at different times in the same place, or (which is the same thing) at the same time in different places, two such influences will cancel each other if they are both of the same intensity and we arrange that one influence arrives at a particular place at the same time as another contrary or opposite influence. If a black band appears in an annihilation experiment it stays so long as the light shines. This shows that once the two influences from the two holes have got 'out of step' at any point they remain so. We deduce that the influence is probably a series of changes following each other at regular intervals.

The Wave Theory of Light

In the foregoing paragraph we have made no assumption whatever about the nature of the influence which we call light, and the reasoning is perhaps inclined to be too abstract to be easily intelligible. We can more easily form a mental picture of the sequence of events in a light wave if we consider what happens when a mechanical disturbance occurs in any material. If the end of a steel rod 3 miles long is hammered once, the shock of the blow arrives at the distant end one second later when this end moves outwards (i.e. in the direction of the original blow). The small particles in the end of the rod are pushed close together in their effort to stop the hammer, just as the pieces of a sponge close their ranks when it is squeezed. Like the sponge, the compressed piece of the rod tries to regain its proper size and pushes outwards at both ends so that the next (uncompressed) piece of rod shortens owing to the force handed on to it by the compressed piece. And so the shock is handed on from piece to piece, every particle moving forward first in the direction of the hammer blow and then returning to its original position when the forces on it are released. It is also easy to imagine the state of the particles along the rod after one end has been given a sudden pull. The particles of all pieces of the rod are now slightly *separated* from each other in turn, but the expansion is handed on just as was the compression due to the hammer blow.

One more step. If the same rod is hit equally hard simultaneously at both ends we have two equal compressions travelling towards the middle of the rod and meeting there after half a second. What happens? The centre particles clearly do not move because they are instan-

taneously pushed in opposite directions by equal forces. This corresponds, in some measure, with the idea of 'equal and opposite influences', and the centre particles will always be at rest (corresponding to darkness) so long as the hammers work simultaneously and do not get out of time.

In applying this mechanical analogy it is important to bear in mind that we have no reason for thinking of light as being in any way due to movements of a *material* like the steel rod: we must try to think of a disembodied disturbance unconnected with the movements of tangible lumps of anything.

To go back to the steel rod, a disturbance may be sent from one end to the other by two ways, other than by the hammer method. These are by twisting and by kinking one end of the rod. When a kinking disturbance travels along the rod each piece bends slightly and passes on the kink to the next piece. The important difference between the way the kink and the blow travel is that, as the latter progresses, each particle moves backwards and forwards *in the direction of the length of the rod*, whereas in the former example the particles of the rod move backwards and forwards at *right angles to the rod.* If one end of the rod is moved regularly up and down a regular series of vertical kinks will pass along the rod, and a similar series of horizontal kinks will travel forward if the end is moved regularly to and fro in a horizontal direction. Now suppose the rod passes through a vertical slit just as wide as the rod is thick. Vertical kinks will pass through, but the horizontal ones cannot because the slit will not allow the rod to move horizontally. This has an important bearing on some properties of light, as will appear shortly.

In imagining light to be a series of vibratory distur-

bances in an unknown medium* Huygens started by thinking of a point of light like a very small incandescent spark. He said that, in an incredibly small time the effect of the spark will have reached out in all directions by equal distances of (say) 1 inch, and that the disturbance in the medium would therefore be a spherical ball of 1 inch radius if it could be stopped and fixed there for inspection. Huygens then thought that each point on the sphere corresponded to a new source of light and after a further equal interval each of these new sources would have sent out an impulse 1 inch further in all directions. The net result of all these little disturbances when added together is another spherical shell, but 2 inches in radius. In practice a sufficiently strong spark would be seen one second later 186,000 miles away by observers at any point on a sphere of this radius; 2 seconds later by all observers 372,000 miles away, and so on, by spherical shells.

The Bending of Light round the Edges of Small Objects

Suppose a small point of light sends out a beam which falls on a threepenny piece and throws its shadow on a screen. The shadow is circular and it is clear to us that light travels in straight lines. Newton thought Huygens was wrong because it seemed to him that, according to the wave theory, light should bend round the corners of the threepenny piece and illuminate the shadow, thus contradicting ordinary experience. Now we know that a high wall or a building will deaden or stop sounds (and thus make sound 'shadows'), while anything small will not be at

* The word 'medium' is here used to convey the idea that it is something not composed of ordinary materials. We like to imagine, however, that it has properties resembling the mechanical properties of objects we are accustomed to handling and about which we think we know a thing or two.

all effective. Since also we are fond of mechanical analogies for things we cannot otherwise picture, may we not suppose that the wave theory is right and that light will turn round the corners of things if they are sufficiently small? In point of fact this is found to be so. Not only will light bend round the edges of small objects, but the centre of the shadow of the threepenny bit is illuminated just as strongly as if the coin were not there. This is a direct confirmation of the idea that each point on the spherical surfaces of the waves acts like a fresh source of light; all the wavelets from the edge of the coin reach the centre of the shadow together and so make the small bright spot. It is perhaps necessary to add that the experiment is difficult to make because minute irregularities in the edge of the disk which throws the shadow are sufficient to spoil the result.

Light consists of Disturbances which are at Right Angles to the Direction of its Travel

A further most important discovery about light was made by Malus,[10] about 1808, when he showed that ordinary white light which comes to us from the Sun can be resolved into two separate sorts of *white* light. This, it must be appreciated, is an entirely different matter from the decomposition of white light into colours by a prism or by the bevelled edge of a looking-glass. It can be shown experimentally that light which is reflected at a certain angle from a mirror cannot be reflected again from a second similar mirror placed at the same angle to the light-ray but twisted about the ray by one right angle. Reference to Fig. 2 will make this point clear. A ray of light PQ falls on the mirror AB (which is seen edge on and is inclined at a certain particular angle to PQ) and is

reflected along the line *QR*. At *R* the ray meets another mirror *CD* inclined to the ray *QR* at the same angle as *PQ* was to *AB*. Now it is clear that we can turn the mirror *CD* about the line *QR* *without altering* the angle between *CD* and *QR*. Suppose we start from the position at which *CD* is parallel to *AB* and we turn *CD* through a right angle about *QR*, then at this point the second mirror kills the ray *QR* and it travels no further.

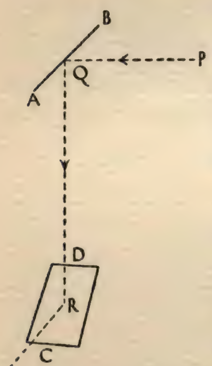

Fig. 2. The extinction of Light by two mirrors

In a preceding paragraph dealing with the rays in which a mechanical disturbance can travel in a solid, it was shown that when a hammer struck a long rod the transmission along the rod was due to the longitudinal motions of the particles of the rod, whereas a kink travelled by transverse motions—i.e. by movements of the particles which were at right angles to the direction of travel of the kink. It was also noted that a slotted plate would only allow one set of transverse movements to pass through it, so that two slots at right angles would stop any movement of the rod beyond the second slot.

There is a strange similarity between these purely mechanical and easily appreciated facts and the extinction of light by two mirrors mentioned just above, and, by reasoning from this and other less direct experiments, it is concluded that the changes in a medium which is transmitting light are at right angles to the direction of the light rays.

Sounds are Disturbances which are in the Direction of Travel

In describing to ourselves the way sounds spread it is easy to picture the to and fro movements of the small air particles as they are pushed by other particles nearer the source of the sound than themselves. Going back to the source itself we can often see, by a certain indefiniteness about its outline, that it is moving and we can also feel its vibrations with our fingers. The air particles nearest a vibrating violin string or loud-speaker diaphragm, or whatever it may be, are set in motion just as the end of the long rod was pushed in by the hammer, and the only differences which need trouble us at the moment are, first, that the string pushes the air many times a second at regular intervals, and second, that the sound travels out in all directions. That sounds are really longitudinal vibrations of some rapidity can easily be shown by an experiment with a cogged wheel which is run at a known number of revolutions per minute. If a visiting-card is held against the teeth of the wheel when it is running fast a fairly musical sound is given out and the note corresponds to the speed. People who live near saw-mills will accept the result of this experiment without any demonstration. If we took the trouble to count the teeth in the wheel and the number of revolutions per second, it would be found that when the card is getting 256 kicks from the teeth in each second the note given out corresponds to the middle C of a piano. The piano string which gives this note makes that number of vibrations in a second so long as the piano is properly tuned. The next C above (the octave) corresponds to 512 vibrations per second, and so on. The ear can hear notes varying from about 20 up to about

20,000 vibrations per second, but it is most sensitive to about 1,500 vibrations per second.

Resonance

There are other effects which are common to all forms of wave motion and one of the most important of these is what is called 'sympathetic vibrations' or 'resonance'. This phenomenon occurs when mechanical vibrations (such as sounds) fall upon anything which is capable of executing natural vibrations on its own account. By 'natural vibrations' we mean vibrations which are given out when an object (bell, wine-glass, or coin) gives out when it is tapped or struck, and since, as we shall see, these mechanical vibrations have their electrical analogies, they are important as an introduction to the less easily understood matters dealt with in Chapter III.

It is well known that a child's swing will, if pushed, continue to swing for some time, like a pendulum, at equal intervals. If we give it a push every time it reaches the nearest point to us, the swings will gradually increase in extent until we find that, push it as hard as we will, we can make it swing no higher.* The two most interesting things to notice are—

(*a*) that we increased the extent of the swings by pushing it at equal intervals, and that this interval is equal to the period of the 'natural vibrations' of the swing;

(*b*) that the swing comes to rest owing to the effects of air resistance, friction, &c., and that the loss of impetus per swing increases with the extent of the swing, as it is natural to expect. Owing to this

* It is assumed, in what follows, that we cannot make the swing rise higher than its supports.

increasing loss of impetus per swing we soon reach a stage beyond which we cannot increase the extent of the swing because we are not strong enough to supply by our pushes more impetus than is required to make up for that which is lost in overcoming the resistances which oppose the motion.

There are many examples of musical sounds which excite sympathetic vibrations of things which are tuned to the same pitch or which, in other words, are capable of vibrating at the same rate. One of the simplest of these is shown by two violins which are in tune. If we sound one of the strings of one of the violins, the corresponding string, and no other, of the second (which may be some distance away) starts vibrating. The vibrations of the string of the second violin may be shown by putting a small piece of bent straw on the string, and the straw will jump off when the corresponding string of the first violin is sounded.

The reason for this is, of course, that the sympathetic string is pushed by the sound-waves from the first violin at the right instants to increase its movements, just as the excursions of the child's swing increased when we pushed it regularly at the right time.

It is often possible to build up a vibration of large extent by very small regular forces which are in tune with the thing which is vibrating, but the extent of the induced vibration is generally limited by resisting forces similar to those mentioned in paragraph (*b*) above. If this were not so all things which 'ring', such as lamp-globes, vases, &c., might be expected to fall to pieces if a corresponding note were struck on a piano, and there would, indeed, be a danger that marching soldiers would break down bridges by the regularity of their tread. In spite of the dissipation which usually sets a limit to the induced vibration, delicate

glass vessels are not infrequently broken by musical notes. One Morhof describes[11] an amusing visit which he paid to a Dutch wine-seller in Amsterdam, who used, so he says, to entertain his friends by breaking wine-glasses, simply by singing the note which was given out by the glass when tapped. The glasses first of all vibrated strongly and then fell to pieces suddenly with a crash. Experiments like these are not easily reproduced at will, but the author has been present on more than one occasion when delicate glass-work was undoubtedly broken by a musical note. The glass did not fall to pieces 'with a crash' but there was a plainly audible click at the moment of fracture.

One electrical analogy of these mechanical effects is shown in all Broadcasting receiver sets. Here, by turning a knob or two, we are accustomed to 'tune in' sending stations which work with waves of different natural frequencies or wave-lengths. The effect of turning these knobs is to alter the characteristics of electrical circuits within the set so that the electricity can move at the required number of vibrations per second. Similarly, by turning the pegs of a stringed instrument we alter the tension of the strings so that they are in accord with the other instruments of the orchestra.

The Meaning of 'Wave-lengths'

All sounds travel roughly 1,100 feet in one second in air and the kind of note makes no difference to this velocity: if this were not so, we might, in large places like the Albert Hall, hear the bass notes of the organ before the strings or vice versa—to the great confusion of the audience, and the ruin of the efforts of the composer. Since the middle C of a piano corresponds to 256 vibrations per second and sound travels 1,100 feet in one second, we must, by

analogy with the steel rod, picture each 1,100 feet between us and the piano as containing 256 places where the air particles are moving forwards, and 256 where they are moving backwards at maximum rates, with intermediate places where they are doing nothing at all at any given instant. The intervals between places where the air particles are doing the same things at the same time are known as wave-lengths and would in the present instance be 1100/256, or something just over 4 feet apart. For the octave above the distance is half this—i.e. about 2 feet. The wave-length of a regular series of waves or ripples on the surface of a pond or on the sea is the distance between two consecutive crests or troughs. Two series of waves will annihilate each other at any given point if three conditions are fulfilled. These are—

(*a*) that the heights of the two sets of waves are equal,
(*b*) that a crest of one series arrives at the point at the same time as a trough of the other series, and
(*c*) that the wave-lengths of the two series are equal.

This last condition ensures that once the waves have got out of step, the two series remain so ever after, and each movement due to one wave is killed by the other at the point of annihilation. We can often observe, near a breakwater or harbour wall, the mutual destruction of two sets of waves on the surface of the sea.

Interference of Waves

It will be appreciated that when two sets of waves are travelling in the same region they will always interfere with each other. This remark applies not only to waves on the surface of liquids, but also to wireless, light, and sound waves. The photographs reproduced in Fig. 3 show strikingly how sound-waves which have suffered reflexion

at a surface affect waves coming from a vibrating source. In the upper photograph we see the outline of a flat right-angled reflector upon which falls a series of waves. The regularly spaced dark lines correspond to the distances* between the waves: where these lines are well defined the incoming waves have been met and destroyed by others which have been reflected from the surface of the reflector. The lower photograph shows the pattern which is produced when a series of waves falls on a cylindrical reflector.

The photographs are interesting from another point of view, and that is their *scale*. After a little thought we come to the conclusion that the waves must have been produced by a very high frequency source because the wave-length is extremely small. The actual frequency of the source was in the neighbourhood of 750,000 vibrations per second—a vibration which is far too 'high-pitched' to be audible. The vibrations passed through oil and the dark striæ were obtained by supporting fine coke dust on a horizontal glass plate in the oil. The dust is heaped up in ridges by the effects of the vibrations and settles at the points where the liquid has no motion—i. e. where the incoming and reflected waves destroy each other. If we had tried to do similar experiments with sound-waves of the pitch of the middle C of a piano the corresponding patterns would have covered thousands of square feet because the wave-length of this note is so much greater than that of the source employed.

* The distances between the striæ are half wave-lengths.

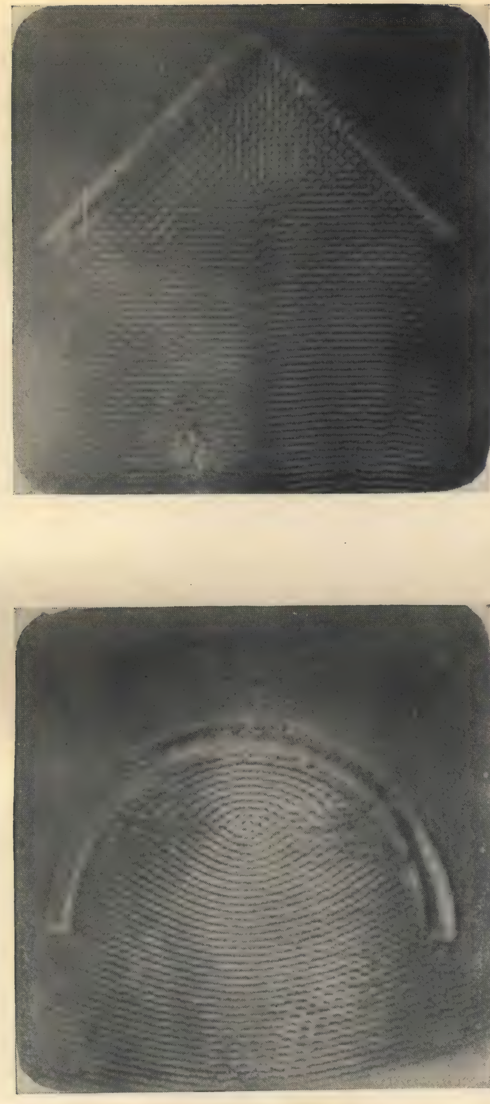

Fig. 3. The mutual interference of two series of waves

Properties of the Ether; Relation between Light and Wireless Waves

Up to the present we have examined some of the properties of light and we have been led to surmise that light is carried at great speed by a medium which is capable of handing on from place to place an undulation which is at right angles to the direction in which the light is travelling. We call this medium the ether and believe that it pervades all space and permeates all substances.

Now light is not the only thing we know that requires an ether to explain how it gets about. Two magnets will attract or repel each other in a vacuum; two electrically charged bodies will do likewise; and the attraction of the earth which causes things to fall to the ground is not in the least incommoded by vacuous spaces or by screens of any kind that we can devise. Are we then to propose a special kind of ether to fill the particular needs of each of these 'actions at a distance'? In this connexion Clerk Maxwell [12] said, 'Aethers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of our bodies to another, and so on, till all space had been filled three or four times over with aethers,' and while it would clearly be absurd to postulate a fresh ether for every occurrence which we cannot rationally explain in any other way, our belief in the existence of a single ether would grow if it could be shown that, by giving it certain hypothetical properties, we could account for two or more of the sets of experimental facts which seem either to demand a medium or to be inexplicable.

There are certain facts about electricity and magnetism which suggest immediately that electrical and magnetic

forces are closely related. The often repeated experiments in which an ebonite penholder or piece of amber picks up light pieces of paper or attracts hairs, show that what we call electric charges exert forces on each other at a distance and indicate that the medium which (we assume) transmits the force must in some way be strained. Faraday[13] imagined that the space between the attracting and attracted objects was filled with an ether which behaves as if it were made up of small tubular filaments connecting the two objects and resembling stretched pieces of elastic or even human muscles—i. e. they always try to shorten and thicken, and, in so doing, pull the objects attached to their ends closer together while they themselves expand sideways to allow for their increased thickness. The ether is 'strained' when any electrical charges are in the neighbourhood—for instance, in an electric accumulator or battery the small filaments cross the gap between the terminals—but the effect of any charge extends in theory through all space, and the movement of the end of a charged penholder entails the movements of these electrical filaments in all directions to the ends of space. This is also true of the forces which are due to a magnet. These extend through all space and change when the magnet is moved.

If we fixed our charged penholder to a wheel and moved it sufficiently rapidly in a circle we should find that a magnet placed at the centre of the wheel would move just as it would have done if we had produced a second magnet and brought it near to the first, so that there is an apparent equivalence between the electric force due to a *moving* charge and the magnetic force due to a *fixed* magnet. This suggests that electric and magnetic forces are strains of some kind in the same medium, and the

idea is confirmed by an observation made by Faraday in 1831, that a *moving* magnet could produce an electric current in a wire held near to it.

These facts, and many others connected with electrical and magnetic happenings, as well as the great mass of existing knowledge about light, were brought under a single ether theory through the genius of Clerk Maxwell. This theory is known as the electro-magnetic theory and it shows that, if we are permitted to assume the existence of a single ether which is capable of bearing electric and magnetic strains, any movement of electricity or of a magnetized body entails changes in the electrical or magnetic forces throughout space. Maxwell also showed, by most brilliant and revolutionary mathematical reasoning, that changes in the electrical forces which surround a charged body are accompanied by simultaneous changes in magnetic forces, and, further, that such changes should be transmitted everywhere in space with a constant and measurable velocity. The electrical and magnetic forces which are thus transmitted act, according to the theory, at right angles to each other and to the direction in which the disturbance travels. Maxwell went even beyond all this and calculated the velocity of these disturbances. This velocity, when translated from its mathematical form into miles per second, was found to be almost identical with the velocity of light as actually measured by Römer and others.

The results summarized in the preceding paragraph were published by Maxwell in 1865 and, at that time, there was no evidence that any disturbances similar to those dealt with in the theory existed in nature or could be artificially produced. It was not until twenty-three years later that Hertz [14] performed certain experiments in which

moving electrical charges were actually shown to generate electrical and magnetic forces in the ether. He proved also that these forces were transmitted to a distance with the velocity of light and that they could be detected by suitable receiving apparatus. The disturbances produced by Hertz therefore had the properties which were predicted by Maxwell and they are identical with the disturbances which are sent out by all wireless broadcasting stations. Incidentally it is interesting to notice that Maxwell's theory explains not only how it is possible for the transmissions of broadcasting stations to be received in our homes but also it contains implicitly the reason for such annoyances as 'fading' and 'atmospherics'. Also the theory shows how the ordinary out-door aerial can pick up distant signals by using the *electric* forces in the wireless signals, while the 'loop' or in-door aerial works by using the *magnetic* forces which are due to the transmitting station and act at right angles to the electric forces. The frame aerial must be set in the direction of the transmitting station because the magnetic forces in the ether are at right angles to this direction.

The following remark, which was made by Maxwell in an earlier paper dealing with Faraday's conception of elastic filaments, is quoted since it shows the attitude of mind which he adopted towards his theories:

> 'If the results of mere speculation which I have collected are found to be of any use to experimental philosophers, in arranging and interpreting their results, they will have served their purpose, and a mature theory, in which physical facts will be physically explained, will be formed by those who, by interrogating Nature herself, can obtain the only true solution of the questions which the mathematical theory suggests.'

In accordance with this remark it is noteworthy that

Maxwell appears never to have attempted to give a physical description of his ether, and it is doubtful whether any adequate conception of it can be formed by the mind. We do not attempt to define what the ether *is*; we recognize it by what it *does*—namely, bears from place to place electrical and magnetic vibrations. The mental difficulty of accepting the ether is considerable, but the necessity of assuming its existence is forcibly brought home to us if we appreciate all that is implied by the sentences which follow. Suppose we are watching the star Betelgeuse through a powerful telescope. We may write down in a diary all that we see happening on the surface of the star day by day. We will further suppose that we see a large eruption or some other notable phenomenon on a certain date, say 28 February 1929. Now that large eruption actually occurred somewhere about the year 1739 by our calendar; the eruption was all over before 1740 and yet we see it in 1929. The question is, 'What happened to the light during the intervening 190 years?' The answer of Clerk Maxwell is, 'The light left Betelgeuse 190 years ago and has ever since been travelling towards your eyes, at 186,000 miles per second, as a wave-like disturbance in an ocean of ether. Your diary of events in Betelgeuse is 190 years behind the time.'

While we cannot say what the ethereal electrical and magnetic disturbances are, or to what physical changes in the ether they correspond, there is still some analogy between these ethereal disturbances, which are at right angles to the direction of travel of the disturbance, and the transverse vibrations of a steel rod, which are similarly disposed. For instance, Maxwell's theory shows that two similar regular series of electromagnetic waves or undulations in the ether will annihilate each other at a point

just as the mechanical vibrations in a rod can be made to do. Such waves will also bend, when they meet the surface of a different medium, by amounts which agree with the bending of light and they will be extinguished by reflection from two mirrors placed at the correct angles to each other.

A spider sitting in the middle of its web is at the centre of an elastic network which is sensitive to any movements of the spider. If the spider shakes itself regularly the filaments of the web are stretched regularly and after a time the trembling of the threads communicates itself to the most distant parts of the network, so that each point of the system expands and contracts in time with the movements of the spider. This movement extends not only over the radial threads of the web but also along the cross-pieces which connect them. An electric charge which moves to and fro causes analogous changes in the ether, and the simultaneous electric and magnetic forces which exist in the ether may be compared with the quivering of the radial and cross filaments of the spider's web.

The identity of the velocity of light and of wireless waves, and the similarity of numerous properties of these disturbances leads to the conviction that they are both attributable to regular wave-trains in the ether and that the only essential difference between the two sets of waves, apart from their size, is that the human eye happens to be sensitive to ethereal waves of the particular lengths emitted by the Sun and other very hot bodies and not to waves of greater or less length. The electromagnetic theory of Maxwell sets no limit to the lengths of the waves which should exist if the theory is right, and it is natural to wonder whether there is, in Nature, a vast range of ethereal waves which are invisible to us only because their lengths

make them unfit for vision. We can produce mechanical vibrations which are too fast or too slow to be heard by the ear because the ear is sensitive only to vibrations which lie between certain limits. We might, then, be prepared to find that there are electromagnetic waves having enormously different lengths, and we shall see that this is the fact.

In considering questions of wave-lengths and the corresponding numbers of vibrations per second it is convenient to remember that the velocity of an electromagnetic wave in space (in miles per second) is equal to the number of vibrations per second multiplied by the wave-length in miles. Since the velocity in space is constant for all wave-lengths, it follows that the longer the wave-length the slower is the corresponding vibration, and vice versa. The acoustic analogy was considered on p. 18.

Different Kinds of Ether Waves

The wave-lengths of ordinary visible light may be calculated from measurements of the distance apart of the dark patches which appear in experiments similar to those made by Young (see page 9), and it is found that waves of light are between (roughly) 30 and 15 millionths of an inch long and the corresponding numbers of vibrations which strike the eye in one second lie between 400 millions of millions and 800 millions of millions. This means that in violet light, which has the most rapid visible vibrations, there are over 65,000 waves per inch and in red light only about half this number.*

* For convenience in writing very large and very small numbers we shall avoid writing numerous ciphers by the use of the following convention:

$$100 = 10^2;\ 1000 = 10^3,\ \text{\&c., so that 2 million} = 2 \times 10^6.$$

Similarly $1/1000 = 10^{-3}$ and 3 hundred thousandths of an inch $= 3 \times 10^{-5}$ inches. Four hundred millions of millions $= 4 \times 10^{14}$.

In 1800 Herschel[15] asked himself whether there were other rays of the same kind as light but invisible to the eye. He had a prism fitted into the wall of his room, so arranged that the coloured spectrum of sunlight fell upon a table, and he placed thermometers on the table so that light of different colours fell upon them. He observed that a thermometer in the red light (slow vibrations) rose higher than others placed in the green and violet (quick vibrations), but the greatest rise was noticed when the thermometer lay in *darkness* on the side of the visible red away from the violet. Herschel believed that these rays, which we now call 'infra-red rays', were of the same character as light, and he showed that they could be reflected and focused by metal reflectors like ordinary light. We now know that infra-red rays are electro-magnetic vibrations which are slower than any visible to the eye and yet very much quicker than the usual wireless waves.

Fig. 4 is a reproduction of a diagram which accompanied one of Herschel's original papers. A large lens was used to focus upon the thermometers the invisible rays coming from the fire, and a comparison of the rates at which these thermometers rose when placed in different positions was used to estimate the amounts of heat radiation focused upon them. The lens acted as a 'burning glass', concentrating the invisible rays just as it concentrates the visible rays.

It might appear, at a first glance, that since white light is decomposed into a number of colours when it passes through a prism, and since the differently coloured beams bend through different angles, the rule of 'least time' (see page 7) is not obeyed. The explanation is that, although light of different colours travels with a constant velocity in space, the velocity in transparent substances generally depends upon the colour of the light.

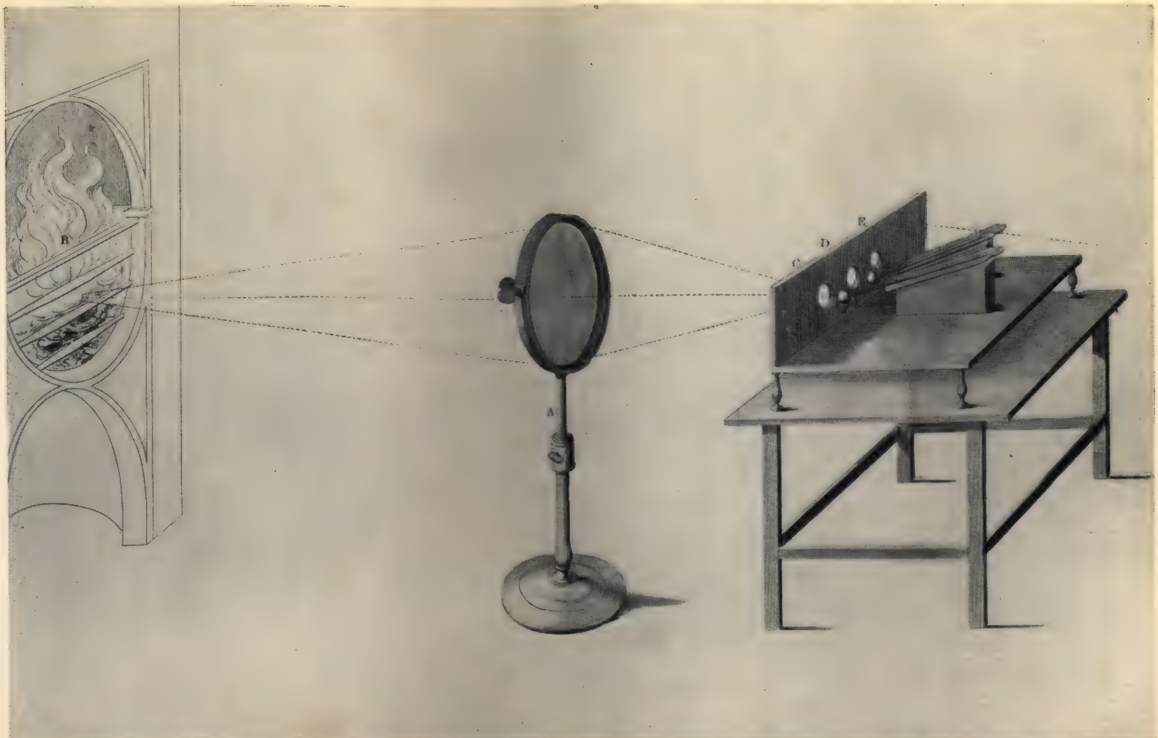

Fig. 4. One of Herschel's methods of examining the properties of the infra-red rays

In glass, for instance, red light travels faster than violet and therefore bends less than violet at the surface of the glass. The truth is then that each kind of light chooses its own path so as to make its course the quickest of all possible courses.

It is important to examine the general properties of the various kinds of electromagnetic waves which have been discovered, and to realize that the only reason for the differences between them lies in their wave-lengths or numbers of vibrations per second. All electromagnetic waves are essentially the same thing and they differ among themselves only as musical notes differ.

The longest electromagnetic waves to which we are accustomed are sent out by certain high power wireless stations. The length of the waves employed depends greatly upon the service for which the sending station is designed, and waves varying between about 20 miles and less than one hundred yards long are in everyday use for wireless signalling. The so-called 'short wave' transmitters employ wave-lengths which may be as short as ten yards, and there is an increasing tendency to use these waves when it is desired to concentrate the signals in certain directions.

It is not possible to focus the very long waves in any desired direction, using transmitting aerials of practical dimensions, because the size of a reflector of any kind of wave, whether electromagnetic or sound, must be large compared with a wave-length before it can be effective. Sounds are not interfered with by small obstacles but are cut off by large ones, and, for the same reason, long-wave wireless signals can bend round mountains.

By using very special electrical arrangements it has recently been found possible to produce wireless waves which are as short as 0·004 inch. These could, owing to

their shortness, be focused by a large metal mirror which would be without appreciable effect upon the longer wireless waves.

Next to the electrically produced wireless waves we have another group called the 'Infra-red'. These rays are invisible like wireless waves, and their wave-lengths vary between about 0·018 inch and 3×10^{-5} inches, which is the limit of visible light. The infra-red rays are emitted by all hot bodies and electric arcs, and the longest infra-red ray which has thus been produced has properties which are identical with those of the shortest electrically produced waves.

Visible light has a range of wave-lengths which lies between roughly 3×10^{-5} inches (red light) and $1 \cdot 5 \times 10^{-5}$ inches (violet light), and beyond the violet we enter into another vast range of invisible radiations which are known as the 'ultra-violet' and extend to waves as short as 4×10^{-8} inches. The reason that waves which are longer or shorter than the extreme red and the extreme violet rays are invisible is that the substances in the light-sensitive layer at the back of the eye are unaffected by longer or shorter waves. We do not know exactly how the visible rays succeed in producing the sensation of light, but it appears that the immediate effect of light upon the eye is to produce a change in certain complex substances in the sensitive area of the eye and that these changes are conveyed to the brain by a system of signal-bearing nerves. Some of the ultra-violet rays are present in the sunlight which reaches the earth, but many of them can only be produced by striking electric arcs between metals. Although they are invisible the longer ultra-violet rays act upon photographic plates, and many substances glow in a striking manner in the dark when 'illuminated' by these rays.

The ray itself, and the source of the rays, may be invisible, but the object upon which they fall becomes visible. This explains why ultra-violet rays are sometimes used for detecting forgeries or reading secret writing. Certain inks, or traces of ink, which may remain in the paper, will glow brightly when illuminated by ultra-violet rays although they cannot be detected when they are examined in ordinary light. It has also been discovered that different parts of the human body glow when exposed to ultra-violet light. The teeth and nails shine brightly while the skin appears a dull chocolate brown. A sudden change of illumination from ordinary white light to ultra-violet light thus alters the whole appearance of a white man and he looks like a coloured one. This phenomenon has an obvious application in theatres and is called the 'negro-effect'.

Shorter waves, even, than the extreme ultra-violet exist. The X-rays and Gamma-rays, which come next in order of shortness, cover a range of wave-lengths from about 4×10^{-8} inches down to 2×10^{-10} inches. Here, again, the longest X-rays have the properties of the shortest ultra-violet rays and the longest Gamma-rays merge into the shortest X-rays. All X- and Gamma-rays penetrate materials, and the shorter they are the greater is the thickness of material they can go through. Like the ultra-violet rays they can also make certain substances glow in darkness.

There is one further group of rays which are still shorter than the shortest known Gamma-ray. This group is known as the 'cosmic' rays because their source appears to be in interstellar space. The results of experiments which were conducted between 1912 and 1928 show that they can outdo any of the previously known rays in their power

to go through solids. Whereas X-rays can penetrate an inch or so of lead the cosmic rays will find their way through a block of lead 18 feet thick. The shortest known cosmic ray has a wave-length of about 8×10^{-15} inches.

Here are, then, a vast number of different kinds of electromagnetic waves varying in length from 20 miles down to 8×10^{-15} inches approximately. Only a strictly limited number of these waves are able to affect the eye, and all the rest are invisible. Some are useful; some we have not learnt to use; but we know the properties of the whole range from shortest to longest. There are no unexplored gaps in which any extraordinary new ray could lie hidden.

This knowledge removes any lingering doubts about the practicability of 'Death-rays': it is impossible to produce any new kind of electromagnetic wave having distant death-dealing powers. Newspaper reports of the discovery of 'mystery' rays often describe the well-known properties of one class or another of invisible rays. It is common knowledge that some of these may be dangerous, especially at short range, but none of them can be the realization of the inventor's dream.

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II
ATOMS AND MOLECULES

Atoms. Molecules. Differences between Solids, Liquids, and Gases. Motions of the particles of substances. Sizes and velocities of the molecules of a gas. Atoms are not simple structures. Relations between electricity and matter. Hints leading to the electrical theory of the structure of atoms and molecules. The idea of energy and its transformation.

Elements and Compounds

IN this chapter we turn, possibly with some relief, from the consideration of waves in an ether about which we can only speculate and never know, to the structure of the materials—solids, liquids, and gases—which we use, see, or touch every day and which seem so common and ordinary that they scarcely need any explaining. Until a very few years ago our knowledge of the different kinds of materials was limited to that which had been painfully acquired by the chemists, who had shown that all materials could be classed either as 'elementary' or as 'compound' substances. The elementary substances were those which nobody had ever been able to breakdown or transform into anything simpler by the means at their disposal, such as grinding, heating, dissolving or melting, and the ultimate particles of these 'elements' were called atoms—which merely means 'things which cannot be cut'. The metals Gold, Silver, Copper, and Iron, the non-metals Carbon and Sulphur, the gases Oxygen and Nitrogen, are all common elements. Altogether, there are at least ninety-two different elements, of which ninety are already known, but many of these are nothing more than chemical curiosities.

It is particularly to be noted that there has never been any guarantee that the atoms of the chemists were in truth

simple structures. In all normal chemical experiments they behave as such, or, as Boyle[1] put it in 1661, 'Corpuscles of a compounded Nature may in all the wonted Examples of Chymists pass for Elementary',[2] and so, for certain purposes and with this mental reservation, we are perfectly justified in looking upon atoms as units in the structure of matter.

In contradistinction to the elements, whose component particles are atoms, we have to consider a vast number of common and uncommon substances which have been resolved into, or built up from, constituent atoms, by chemists. If, in imagination, we divided a grain of a compound such as common salt, we should eventually reach a stage at which we were left with a thing we call a single molecule. This molecule is the smallest particle of salt which can exist and yet keep the properties—saltness, &c.—which we associate with common salt. If we split this molecule we should be rewarded for our pains by the appearance of two atoms—one of an element, Sodium, and the other, another element, Chlorine. Sodium is a greyish metal, and Chlorine an evil yellow gas. We need not be unduly surprised that two such unlikely substances should be within the salt-cellar, because a molecule of salt is a self sufficient salt-unit and does not give any directly recognizable sign of its concealed inhabitants. Nor, for that matter, does a Chinese manuscript easily yield its hidden meaning to the uninitiated.

The idea that materials are made of numbers of minute particles was first put forward in definite shape by Leucippus and Democritus. The contrary idea, expressed in the doctrine of homoeomeria, was to the effect that matter is essentially continuous and infinitely divisible, and is the same in its smallest parts as it is in bulk. The difficulties

of the latter idea are great and it was long ago discarded as a useful working hypothesis.

The theory of Democritus was upheld by Lucretius in a poem,[3] parts of which might easily have been written fifty years ago, so accurately is the modern conception of the chemical atom fore-shadowed. The following lines, which have been taken from a translation, express the idea which we have just outlined in the first paragraph of this chapter: 'First beginnings are of solid singleness, massed together and cohering closely by means of least parts, not compounded out of a union of these parts, but, rather, *strong in everlasting singleness.*'

The present form of the atomic theory—so far as chemistry is concerned—is due to Dalton,[4] who believed that 'the ultimate particles of all homogeneous bodies are perfectly alike in weight, figure, &c.', and that the differences between the properties of the elements is due solely to the different 'weights, figures, &c.' of their atoms.

We can go a long way towards explaining the properties of materials by assuming the existence of different sorts of atoms resembling minute, impenetrable, and indestructible billiard balls, which are capable of attracting all other atoms and of adhering more or less strongly and constantly to each other when they form parts of molecules. The atoms of Hydrogen and Chlorine, for instance, generally go about in pairs (molecules), being kept together by some attractive bond, and they will remain thus indefinitely. If equal volumes of Hydrogen and Chlorine gases are mixed, the two original partnerships break down and we are left with a fresh gas (Hydrochloric acid gas), each molecule of which contains one atom of Hydrogen and one atom of Chlorine. It is just as if the Sisters Smith and the Brothers Brown, having been mutually

inseparable, meet. It may be that after the meeting the two partnerships are dissolved and replaced by two fresh and more enduring ones. These exchanges may be written thus, after the manner of chemists:

H-H	+	Cl-Cl	=	2 H-Cl
or Brown-Brown	+	Smith-Smith	=	2 Brown-Smith.

The hyphens between the 'atoms' signify the existence of bonds of attraction between them. The chemist explains the willingness to change partners by saying that the attraction or 'affinity' of the two different kinds of atoms for each other is greater than their attraction towards other atoms of their own kind. He does not necessarily make any statements about the real reason for the existence of the attractions.

Many hundreds of thousands of chemical compounds have been made and analysed: all these measurements agree with the view that no molecule ever contains any fraction of an atom, so that we have the strongest reason for thinking of atoms as the bricks of which materials are built.

The Kinetic Theory

In recent times great progress has been made with mathematical theories which deal with the movements of the particles (atoms or molecules) which make matter, and these theories teach us that the ultimate particles of all substances are in constant movement and that the rate of this movement increases with a rise of temperature. A piece of silver is ordinarily bright and reasonably strong, but it can be changed into a liquid, or even into a gas, by melting or boiling. The solid, the liquid, and the gas are all nothing but pure silver, and the theories to which we have just alluded show us how we may easily account for

the very marked differences between a silver bar and a volume of gaseous silver.

According to the theory, we are to look upon the movements of the particles of the solid silver bar as very small, and we imagine that, owing to the closeness of the packing, the atoms or molecules attract each other so strongly that they are rarely able to leave their normal positions, and such movements as they have are mainly confined to vibrations about more or less fixed positions. When we heat a silver bar it expands owing to the assimilation of some of the heat; this is taken up by the vibrating particles of metal and increases their average range of movement. If we go on heating the bar until it melts, the increasing movement of the silver particles reaches a point at which their endeavours to free themselves from their local attractions are satisfied to the extent that all the particles are free to move anywhere inside the liquid, but each one is still closely hemmed in by its neighbours and heavily jostled by them. After a further rise of temperature the liquid becomes a gas. The agitation and the excursions of the particles are then so great, and their collisions with their neighbours are so violent, that the mutual attractive forces between them are nearly negligible. The atoms or molecules in gases are thus far more independent of the effects of their companions than in either other state, and their freedom has been acquired by virtue of heat, which has been transformed into violent movements, but may be regained by allowing the gas to cool until it is once more a liquid and then a solid. The internal movements have then died down and the heat has gone elsewhere.

It may perhaps be a little difficult to accept the view that the small parts of all things, even of solids, are in movement. The following remark, which was made by Hooke,[5]

is very much to the point: 'Nor can I believe indeed that there is any such thing in Nature, as a body whose particles are at rest, or lazy and unactive in the great Theatre of the World, it being quite contrary to the grand Oeconomy of the Universe.'[6] Normally we see no sign of these internal movements, but if we remember how quickly a scent will permeate the air of a room, without any draughts to hasten the diffusion, we can easily picture the small scent particles shooting about from point to point among the molecules of the air, pushing them and rebounding, and not being satisfied until they have distributed themselves throughout the air of the room. It is easy, too, to demonstrate the internal strife between particles in a liquid, because it happens that we can make the movements visible. Gold may be dispersed in an extremely finely divided state in a liquid and the movements of the gold specks can be seen, under strong illumination, with a microscope. We may watch them, as points of light, moving jerkily from place to place, being pushed and pounded by the liquid particles among which they are suspended, and never ceasing their dance however long they are left. Their exhilaration is seen to be greater or less, according to the temperature, as theory teaches us to expect.

So far, so good. But do these movements really occur in solids? Once the idea is given and explained it is comparatively easy to admit its validity in mobile liquids and tenuous gases. But in solids—? No, it sounds too far-fetched. In spite of the common-sense man's denial, the particles of solids are undoubtedly in continual movement, as was proved in 1896 by Roberts-Austen, Chemist and Assayer of the Royal Mint. He took blocks of Gold and of Lead and pressed their smoothed surfaces together so that there was good contact between them. They were

left thus for some time and then separated. The outer surfaces of the blocks were shaved off and it was found that Gold had gone into the Lead block and Lead into the Gold—not very far, it is true, nor in any great quantity, but enough to show that the particles of solids are moving about and are not fixed in place once and for all.

We are unable here to discuss further the wide applications of theory to the movements of the particles of materials, but it is easy to see that the conduction of heat along a poker, the evaporation of liquids and solids, and the resistance of all things to compression, may be explained by the use of the hypothesis enunciated on p. 38. Consider for a moment the conduction of heat. In the hot end of a poker the particles are in more rapid and violent movement than their neighbours in cooler spots, and they pass on a share of their agitation. Eventually the handle of the poker will be full of particles which painfully bombard the hand of any one who tries to pick it up, the sensation of heat being due purely to the unusual violence of the movements of the molecules in the poker. The vibrations of the molecules of a road shaken by heavy traffic do not give us a sensation of heat any more than very slow vibrations of a string will produce a sound, since both are too slow. It is, however, possible to set materials into very rapid mechanical vibration. When these vibrations reach some hundreds of thousands per second they are quite inaudible, but the vibrating material feels hot and will raise blisters on the skin. The heating of the head of a nail which one is hammering is clearly due, according to the theory, to the increased movement of the iron particles which have been thoroughly shaken by the blows of the hammer, and we conclude that the temperature of a body depends upon the random movements of its mechanical parts.

In order to obtain some more definite ideas about atoms and molecules, as conceived by the chemists of the last century, it may be well to examine some information which is at our disposal concerning their sizes, speeds, and other habits.

It might at first appear that the theory of molecular and atomic motions, which was outlined on pp. 38–9, is an unpromising field for accurate calculation. The mere assumption of any kind of haphazard molecular movement would, one might not unreasonably assume, be enough to remove any hope of deducing numerical results, as opposed to matter for purely qualitative discussions, relating to common phenomena. Now it is a peculiar thing that nothing is more certain than the average result of a large number of random happenings. While we cannot say with any certainty how long a particular individual will live, the Insurance Companies have most reliable figures to tell them how long people live on the average. Over a short number of years and assuming no fresh factors—a war, for instance—intervene, we can be confident that this average will not alter appreciably. The greater the population the more certain may we be of the average life-time of individual members of it, and in our dealings with matter in gross we can be confident of the laws of physics because they are average laws. The 'miracle' may only be the unusual event which must turn up occasionally, like thirteen trumps in one hand at Bridge.

It is accordingly not *impossible* that the water in a kettle will freeze when placed upon the fire and no scientific theory would be violated if it did so. Mathematicians tell us that freezing is most unlikely simply because the chance of boiling is immeasurably greater than the chance of freezing. The chances of either event are reckoned from

considerations of the relative numbers of ways the water can get hotter and the fire colder, and vice versa. A mathematician will be prepared to give the odds against the freezing of the water in the kettle and they are so great that we confidently assert that the kettle will boil.

The Sizes and Velocities of the Molecules of a Gas

And so with the movements of the molecules of gases. Here we have a vast army of minute particles, free, we assume, from any forces except those due to their impacts with each other and with the walls of the vessel which contains them. Their movements are thus subject only to the laws of chance. We do not know a single thing about the actual speed or direction of motion of any individual particle at any time, but, by the use of the theory of probability and some simple geometry, we are able to calculate with great accuracy the average velocity of each molecule between impacts with other molecules, the average distances they travel between impacts, their masses, sizes, and numbers per cubic inch. Theories such as these are the result of the joint labours of mathematicians and physicists and it is lucky for science that Trade Union rules do not apply to their work, for in physics neither can get on without the other and each one has to practise the other's trade.

If, then, we borrow the mathematician's tools for a little while and calculate the average distance which the molecules of Air (or of Oxygen—it is roughly the same for both) travel between collisions, we find that it works out at something like 4×10^{-6} inches only. For Hydrogen it is greater, but still only 7×10^{-6} inches. These figures depend, of course, upon the temperature and the degree of compression of the gas, and so, for the sake of uniformity, the

figures we give apply to certain standard conditions. In order to form an estimate of the size of the Oxygen molecule we remember that when we liquefy any gas, either by cooling it or by compressing it, or by a combination of both, a large volume of gas will be found to yield only a few drops of liquid. It is then most obvious that, on the average, the molecules in a gas must occupy more space than they do in a liquid. By darting in all directions at random, a small hive full of bees can effectively 'occupy' a large room or even a much larger space, and they certainly do not change their individual dimensions in order to do it. Nor, we imagine, do the molecules of a liquid when, as gas, they occupy a space which may be 1,000 times as great as it was when they were more closely associated; it is only the average space between them that alters. For the purpose of making a rough calculation of the size of a molecule we shall assume that liquid Oxygen, for example, if looked at under a sufficiently powerful magnifying glass, would resemble a jar of lead shot—the molecules all being spherical and touching. Now liquid Oxygen is about 1,000 times as dense as the gaseous Oxygen of the air—that is, the molecules are 1,000 times more densely packed—and hence the radius of a molecule must be in the neighbourhood of a thousandth part of the average distance which each gaseous Oxygen molecule has to travel before it hits another—viz. 4×10^{-6} inches. The radius of an Oxygen molecule is thus about 4×10^{-9} inches, or it would take some 125 million of them placed in a row to stretch an inch. This is an exceedingly crude way of estimating the size and is interposed here merely to show the approximate order of the magnitudes involved. The figures obtained are, however, very roughly right.

By the same theory we may work out the average

velocity of the Oxygen molecules between collisions, their weights, and the numbers of them per cubic inch. The first and last are large quantities, viz. about 17 miles per minute and 4×10^{20} per cubic inch. The weight of a single oxygen molecule is correspondingly small, viz. 8×10^{-22} grains.* The number of molecules per cubic inch is the same for all gases at the same temperature and pressure, but the velocities of light molecules are always greater than the velocities of heavy ones, other things being equal. In spite of the great velocities of the air molecules we feel nothing of them because they move at random in all directions in the body of the air. The chances are very greatly against any number of them starting off in the same direction at the same time (a 'miracle'), but if they did we should feel a gale of unimaginable violence.

The atomic theory ranks as one of the greatest achievements of chemistry, for it has provided a simple reason for the observed constancy of the proportions of the chemical elements found in compounds, and it has pointed the way to explanations of many other phenomena in which no violence is done to the atoms themselves. Science, however, could not rest content with a system of 92 elements which, in order to be different, must themselves have some complicated structure. There has always been at the back of men's minds the idea that, if the truth were known, we should find that the so-called elements are made of different arrangements and quantities of a very few primary substances. Knowing what these substances are and how they are put together inside the atom, we should be able to transmute the elements and build them out of their simpler constituents. Thus we find that Empedocles believed that

* A grain is 1/7000th of one lb. avoirdupois.

there were only four primary elements, air and fire, earth and water, while the writings of the pre-Renaissance alchemists show that similar beliefs lay behind much of their work.

Within the Atom: Connexions with Electricity

And so, when, during the last century, accurate knowledge of the relationships between the weights of the atoms, which was derived from the results of many analyses of chemical compounds, had accumulated, we find scientists scrutinizing these figures in the hope of finding in them some regularity or clue leading to the discovery of a sub-atomic unit, or units, common to all elements. Many peculiar and inexplicable arithmetical relationships between the relative weights of the atoms were discovered. They appeared to lead nowhere, but, in 1859, we find Strecker discussing some of these arithmetical curiosities and remarking,[7] 'We can hardly suppose that all these relations between the atomic weights of chemically similar elements are the results of mere chance, but we must leave to the future the discovery of a reason for them.'

A most remarkable series of generalizations, bearing directly upon the structure of the atom, was made in 1869 by Mendeléeff,[8] and we extract the following conclusions because they are now easily explained by a theory which we shall shortly examine:

'I. The elements, if arranged according to their atomic weights, exhibit an evident *periodicity* of properties.

'II. Elements which are similar as regards their chemical properties have atomic weights which are either of *nearly the same value or which increase regularly.*

'V. The magnitude of the atomic weight determines the character of the element....

'VIII. Certain characteristic properties of the elements can be *foretold* from their atomic weights.'

As an illustration of the strength of these rules, it is interesting to note that Mendeléeff was able to predict the approximate atomic weights and properties of unknown elements. His predictions were fully verified when, years afterwards, the new elements were eventually discovered.

Our present knowledge of the structure of atoms has been obtained by following up hints which Nature has occasionally dropped to inquirers, and by applying the increasingly perfect instrumental aids by which men have been able to sharpen their powers of observation. One such hint was received by Faraday in 1834. He found that when an electric current is passed between two plates held at a distance apart in a bath containing dissolved metallic salts,* the weights of the metals which are deposited on one or other of the plates † are, other things being equal, very simply related to the atomic weights of the dissolved metals. If we weigh the actual amounts of metal brought out of solution by the current and measure the quantity of electricity which has passed—that is, the intensity of the current multiplied by the time it flows—we find that the atoms of different kinds of metals behave in solution as if each one were attached to an electric charge of definite size. The same total amount of electricity always deposits the same amount of silver whether it passes quickly or slowly through the silver solution, and this relation between quantity of electricity and weight of silver deposited is so accurate that it is used as a standard method of determining the values of electric currents. If we like we may look upon the atoms of metals as a number of baskets each containing identical small numbers of melons. If twenty baskets arrive at our door and are

* e.g. copper sulphate (blue vitriol) or nitrate of silver.

† This is the process of electroplating.

emptied there we can tell, by counting the baskets, how many melons there should be, or vice versa. Similarly there is an exact relation between the amount of electricity which arrives at one of the plates in an electroplating bath and the number of atoms (baskets) deposited. It does not matter whether the baskets arrive one each day by separate messenger boys or whether they all arrive in the space of a few minutes—the relation between the number of melons and the number of baskets is the same. Not only metals, but all the elements, obey this suggestive rule.

Faraday's experiments lead us to the conclusion that both positive and negative electricity exist in Nature in multiples of certain units, which are associated with the chemical atoms in an intimate way. Helmholtz,[9] lecturing in 1881, said, 'If we assume the existence of chemical elements, then it follows (from Faraday's researches) that both positive and negative electricity are divisible into definite elementary quantities, which behave as *atoms* of electricity.'[10]

It is well known that when different substances are strongly heated or passed into a flame, light of various colours may be produced. Common salt colours a flame yellow; Strontium salts, red; Copper, green; and so on. The suggestive thing about these colours is that they depend upon the presence of the elements Sodium, Strontium, and Copper, and we observe the same colours whatever compound of these elements is selected. The colour of the light is then intimately connected with some property of the atoms themselves, and probably on some internal property, as otherwise it would most likely be altered when the atom is combined with another atom or atoms.

The colours of those common red and blue electric signs which are made of plain glass tubes containing small

quantities of the rare colourless gases Neon and Helium have essentially the same origin as the colours emitted by heated substances. The activity of the gases in the tubes is, however, brought about electrically instead of by the action of heat.

Now we have seen that light is a vibration of the ether and that each differently coloured light has its own particular number of vibrations. It is thus most natural to suggest that there is something inside the atom which vibrates with a frequency which is the same as that of the emitted light, just as the sound of a particular note can always be traced back to something vibrating at a corresponding speed. Here is another hint that the atom of the chemist is not an indivisible unit. Taking into consideration the experiments of Hertz on moving electric charges (Ch. I, p. 24), we may well infer that the vibrating portions of the atom are electrically charged.

Some of the most revolutionary discoveries about the structure of atoms were made by studying what happens when a powerful electric battery is connected to two plates sealed into a glass tube from which nearly all the air has been pumped. The connexion to the plates is made by wires fused through the glass and portions of the inside of the tube and its walls shine when the battery is connected. The glow on the walls of the tube is always opposite the plate which is connected to the negative terminal of the battery, and it disappears if anything is placed inside the tube between the negative plate and the part of the tube which should light up. A little 'wind-mill' placed inside the empty tube between the two plates is driven round when the current is turned on, although it is touching nothing and is in a high vacuum. Observations like these led to the suggestion that the glow on the walls of the tube and

the movement of the wind-mill were due to the bombardment of the tube and the sails of the mill by a new kind of rays which were called 'cathode rays' because they started from the negative plate or 'cathode'* of the tube. These rays are peculiar in that, unlike light or ordinary electromagnetic waves, their course towards the wall of the tube is deflected by bringing a magnet or an electric charge near the tube. But it has already been seen in Chapter I that a moving electric charge exerts a force on a magnet, and consequently we may explain the deflexion of the cathode rays by assuming that they are flying electric charges. These two ways of deflecting cathode rays were used by Sir J. J. Thomson[11] to show that the cathode rays are simply negatively charged particles which are urged through the empty tube under the influence of the electrical pressure of the battery.

The principles upon which the deflexion method of measuring the masses and charges of the cathode rays are based are easily understood if we remember that it is less difficult to alter the course of a tennis ball than that of a projectile moving at 2,000 feet per second. The greater the velocity or the mass of the moving body the greater is the force required to deflect it. When we attempt to deflect the cathode rays we use electrical and magnetic forces instead of mechanical ones, and from a knowledge of their intensities and the extent of the deflexions they produce, we are able to calculate the relationship between the mass and charge of the particles.

Fig. 5 is a picture of a tube used for the deflexion of cathode rays. In it are seen the cathode from which the rays come, a pair of perforated plates which serve to make a narrow 'beam' of rays, the two electrically charged

* Greek, *kata*, down; *hodos*, a way.

plates which deflect the beam, and the luminous* patch *P*, where the deflected rays hit the glass wall of the tube.

Sir J. J. Thomson succeeded in showing that these particles move at speeds which may be as high as 1/3 of the velocity of light, and—more important still—that they are the same whatever material is used for the cathode plate from which they come. The quantity of electricity on each particle is identical with those small units of charge which were found on the atoms of metals in Faraday's experiments, but it is opposite in kind and is called 'negative'. The names 'positive' and 'negative' which are applied to electric charges indicate that two opposite charges will attract each other, and it is purely a matter of convention which kind is called 'positive' and which 'negative'. The terms came into use in the early days of electrical experiments when it was found that if a piece of sealing-wax is rubbed with flannel the charge on the wax attracts the charge on the flannel, but two charged pieces of wax repel each other. The charges on the flannel were called positive and those on the wax negative.

With the discovery that all materials contain identical units within their structure, scientists believed that they were at last approaching a long-sought goal. It seemed that the negatively charged particles were possibly the ultimate and indivisible units in the structure of matter which atoms had formerly been thought to be. After what has been said about the atom, readers will not lightly assume that the negative particles which are common to all atoms are necessarily simple units, but will be willing to admit that it is fair to regard them as units so long as

* It must be remembered that the cathode rays are not themselves luminous, but they often produce light when they strike materials or pass through gases.

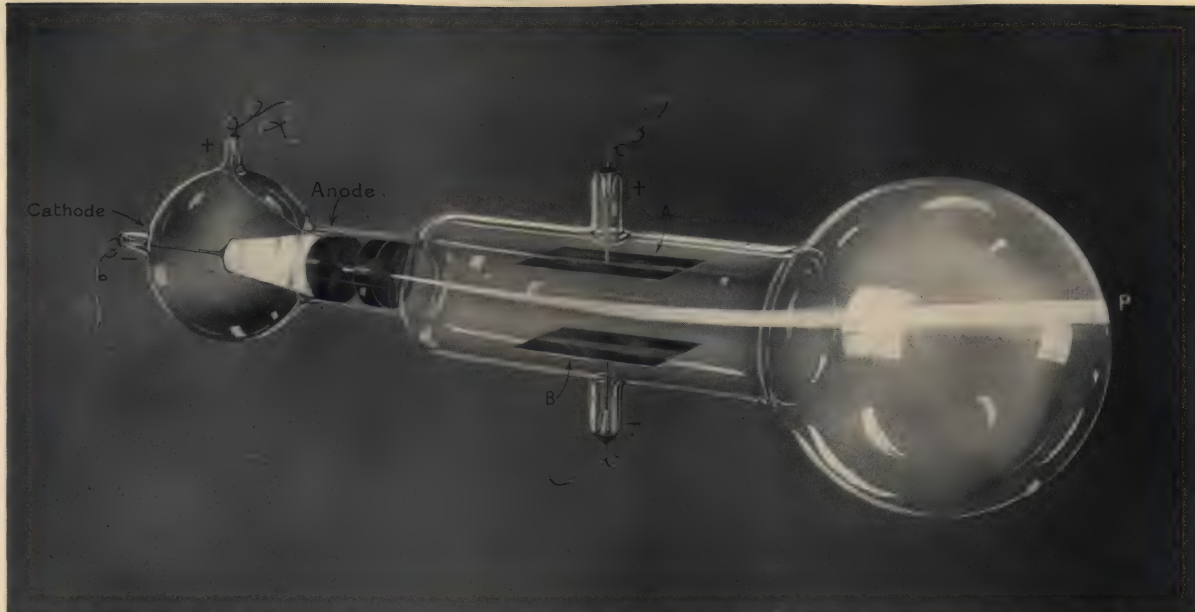

Fig. 5. A tube used for the deflexion of Cathode Rays

we find no evidence to the contrary. Some points from the most recent speculations concerning these negative particles are discussed in Appendix I.

In addition to the moving negatively charged particles, moving positive charges have also been found in vacuum tube experiments. These charges are found to be identical with the unit charges on metal atoms in solution, but their velocity is much smaller than that of the particles of cathode rays. The reason for this difference is that the cathode ray particles behave as if they had only an exceedingly small mass (about 1/1835 of that of a Hydrogen atom), while the mass associated with positive charges is always much greater than this and is in fact equal to that of ordinary atoms. The light particles have a much better chance than the heavy ones of working up a considerable speed in the tube, just as a light motor-car with a powerful engine can accelerate more quickly than a heavy lorry with a similar engine. The mass associated with positive charges found in these experiments is not constant: it depends upon the kind of gas particles which remain in the vacuum tube, and we are led to believe that the carriers of positive charges are atoms of ordinary matter.

About the time that Thomson was busy with his work on cathode rays Becquerel[12] was examining a number of substances which emitted light under certain conditions, and, by accident, he discovered a new kind of ray which fogged a photographic plate through the ordinary opaque shutter. The particular substance which surprised Becquerel contained the element Uranium, which is now classed with a number of other substances (Radium, Actinium, Thorium, &c.) known as 'radio-active'. Not many years later Sir Ernest Rutherford[13] showed that radio-active substances are continually emitting three

kinds of rays which we call Alpha-, Beta-, and Gamma-rays, and that, of these, the Alpha- and Beta-rays are in reality rapidly moving positively and negatively charged particles, while the Gamma-rays were soon shown to be invisible electromagnetic waves of the same kind as light and X-rays, but shorter than either. Further work upon the Alpha-rays indicated that they are similar to the positive rays of the vacuum tube experiment, but they travel very much faster and all the particles have the same mass, which is, in point of fact, almost identical with that of the atom of Helium—a rare gas which is found in the atmosphere and is, next to Hydrogen, the lightest element. The Beta-rays are identical with the cathode rays, but instead of travelling with a maximum velocity of about 1/3 that of light they come out of some radio-active substances with speeds which may be greater than 185,000 miles per second, which falls little short of that of light itself. In order to avoid confusion and to fix our attention on the fact that Alpha- and Beta-rays behave more like small charged particles than anything else we can imagine, we shall refer to them as Alpha-particles and Beta-particles, remembering that the Alpha-particles are massive things compared with the Beta-particles, and that the former are associated with two positive charges while the latter have only one negative charge.

The Electrical Constitution of Matter

It was Sir Ernest Rutherford who summed up all these observations and arranged them in an intelligible order. He took the very broad hint which Nature had given him through the phenomena of radio-activity, combined with the less direct ones which had been given to previous workers, and formulated, in 1911, the electrical theory

of the structure of matter. In it he substitutes for the hard impenetrable atoms of Dalton, nothing more than systems of negative charges (electrons) which rotate round a central positive charge (the nucleus) just as the planets revolve round the Sun. This conception of the atom was backed by observations which made it more complete and more consistent than any similar theory which had previously been proposed, but we may give credit to Bacon for what may be interpreted as a remarkable guess. Bacon says:[14]

> 'he who shall duly attend to the appetences and general affections of matter (which both in the earth and heavens are exceedingly powerful, and indeed pervade the universe) will receive, from what he sees passing on the earth, clear information concerning the nature of the celestial bodies; and, contrariwise, from motions which he shall discover in the heavens, will learn many particulars relating to the things below, which now lie concealed from us.'

In considering Rutherford's theory it is essential to remember three things. One is the idea that atoms have an electrical structure and are made of electrical charges moving in certain definite ways; the second is that the negative electrons within the atoms are identical with the Beta-particles thrown out by radio-active substances and with the so-called Beta-rays of the vacuum tube; the third is the assumption of a central positive charge which is mainly responsible for the mass of the atom. Positively charged particles may, like the Beta-particles, be removed from atoms by the action of electricity in a vacuum tube, and they are, in fact, the 'positive rays' which we have recently mentioned. An Alpha-particle is one particular kind of positive ray of great velocity. We believe that Alpha-particles are the positive centres of Helium atoms and that they are expelled from the nuclei of radioactive atoms under the influence of some internal upheaval

which is so deep-seated that we cannot stop it or even modify its relentless course.

In the next chapter we shall see how the Rutherford atom can be made to explain the observations which have been noticed in the preceding paragraphs of this chapter concerning electrolytic action, coloured flames, electrically excited light from gases, and radio-active phenomena, as well as the regularities noticed by Mendeléeff in the properties of the chemical elements.

The Conception of Energy

Before we begin the next chapter it will be well to answer a query which must already have entered the mind of the reader. This is—

'What do you really imagine happens when, for instance, you strike a nail on the head with a hammer and observe that the nail is hotter than it was? The hammer I have looked at carefully and weighed. So far as I can see neither it nor the nail has changed appreciably—the nail is a little flattened perhaps, but I cannot see how this explains what it is that the hammer gave the nail which made it hot. Nor, for a matter of that, am I clear, when you speak of vibrating electric charges emitting light, what it is they lose which is apparent to us as light.'

The answer to this and all similar queries is, 'There is a transference of ENERGY'. The word Energy is in every-day use and, when applied to individuals, often means an unseen power of getting things done. Many people, of the actively energetic variety, always seem to be rushing about doing things and infecting others with a similar activity. There is another class who are subconsciously felt to be charged with energy which is latent and only waiting for some impulse to make itself manifest in the active form.

There are parallels to this in Science. The energy of a body is its capacity for doing things, and may be due

either to the motion of the body or to its position. A bullet in flight (actively energetic) differs from a bullet at rest only in the energy which it possesses. This energy makes it possible for the bullet to 'get things done'—it can penetrate a steel plate or knock a hole in a door. If we carried a similar bullet up a mountain and held it still over a precipice 10,000 feet high it would seem harmless and inert, but it actually has latent energy which we have given it by carrying it up the mountain. If we let it fall it would reach the earth 10,000 feet below with a speed of 800 feet per second and we should admit, if it hit us, that it was full of energy.

Now it is an axiom of science that energy can never be destroyed, but that it can change its form. The latent energy of a bullet clearly depends upon its position and is known by the term 'potential energy'. The active form of energy is known as 'kinetic' and is measured by the product $1/2\ mv^2$, where m is the mass of the moving body and v is its velocity. Suppose the hammer which hits the nail weighs 2 pounds and is moving 10 feet per second at the instant of the impact. If the hammer stops dead it has lost $1/2 \times 2 \times 10^2 = 100$ units of energy, and some of this energy divides itself up among the many particles in the nail-head and hammer, whose energy of random movement is thus increased. Another portion of the energy of the hammer has been used up in overcoming the resistance of the wood or other material into which the nail is fixed. Yet another fraction has been given to the surrounding air and dissipated in the form of the sound of the blow. Sounds are, as we have seen, vibrations of air particles and are therefore a form of energy.

If the total energy after the impact could be gathered together again and put back into it as kinetic energy, the

hammer would again be moving at 10 feet per second. Again, since no energy is ever lost, the sum of the potential and kinetic energies of the bullet which was taken up the mountain is always constant as it falls. When it is at rest at 10,000 feet its energy must be equal to its kinetic energy at the bottom of the precipice, because its energy of motion is only another manifestation of the latent energy it had when at rest at the top.

The Transformation of Energy

We have already stated that energy can change its form but never be destroyed. As an example of the transformation of energy we may consider what happens to the coal which is taken to a power station. The coal is burnt under a boiler and part of its energy is converted into heat energy in the flames which go through the boiler tubes. Some of this heat passes into the water which boils owing to the increased agitation of its molecules. The active steam molecules surrender some of their energy to the turbine wheel which drives a dynamo, and the energy then appears as an electric current. The electric power can be converted into light energy in a lamp, back to heat energy by an electric radiator, or into mechanical power by a motor. It can also be stored in an accumulator as chemical energy and recovered again as electric energy—there is practically no limit to the changes that we can bring about.

When one pushes a lawn-mower, the total energy expended, or the work done, will depend upon the force required to push the mower and the distance it is pushed, or, in other words, energy is the equivalent of *Force* multiplied by the *Distance* through which the force moves. The potential energy of the bullet at the top of the mountain, reckoned with respect to a zero position at the

bottom of the mountain, is equal to the energy expended, or the work done, in lifting the bullet to the top of the mountain; that is, the weight of the bullet multiplied by the height of the mountain.

Energy in the Ether

When we consider electric charges, such as those obtained by rubbing pieces of amber, it is clear that there is energy associated with them because they are capable of setting things in motion by their attractions. Suppose we start with positively and negatively charged bodies close together and we separate them. There is an attractive force which opposes this separation and we do work, or use up energy, in overcoming this force. If, after having separated the two charges by a certain distance, we stop and let the charges free, they will rush together and acquire kinetic energy, which must, at the moment of impact, be the equivalent of the energy we have expended in separating them, since energy cannot be lost but only change its form. We may ask where is the energy which is associated with two attracting charges, when they are held at a certain distance apart and prevented from moving. The answer is that this potential energy is latent in the ether, which may be regarded as being in a state of tension between the two charges. An india-rubber band which is stretched must have a similar latent, or potential, energy because the ends, if released, will fly together and develop kinetic energy corresponding in amount to the work done during the original process of stretching it.*

* The conception of energy is an important one for mathematicians and physicists, and some of the most remarkable 'long shots' have been made by manipulating equations which express energy relationships. The idea is not an easy one to acquire, but we must not complain if those skilled in the mathematical game choose to use clubs of uncommon pattern.

According to classical ideas an electric charge vibrating at a certain frequency should emit light. Some of the energy of the charge would appear as radiant energy in the ether and we should see, if such a gradual process of energy emission took place in Nature and we could watch it, that the movement of the emitting charge diminished owing to the loss of energy just as the movement of a pendulum decreases because energy is given to the surrounding air particles. In point of fact this image of the production of light is faulty and a better explanation will be given in the next chapter.

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8. Dmitri Ivanovitch Mendeléeff. Born at Tobolsk, 1834. Professor of Chemistry at the University of St. Petersburg. Died 1907.
9. Hermann Ludwig Ferdinand Helmholtz. 1821–94. Born and died at Berlin.
10. *Vorträge und Reden.* Vol. 2: 'Die neuere Entwickelung von Faraday's Ideen über Elektricität.' (Braunschweig, 1903.)
11. Sir Joseph John Thomson. Born near Manchester, 1856. Cavendish Professor of Experimental Physics at Cambridge, 1884–1918.
12. Antoine Henri Becquerel. Born in Paris, 1852. Died in Brittany, 1908.
13. Sir Ernest Rutherford. Born in New Zealand, 1871. Now Professor of Experimental Physics at Cambridge.
14. *De Dignitate et Augmentis Scientiarum.* Book 3, ch. 4.

III

THE ELECTRICAL STRUCTURE OF ATOMS AND THE PRODUCTION OF RADIATION

The Rutherford model. Production of light by Hydrogen. Quantum jumps. Quantum principle. Disruption of atoms. Rutherford models of complex atoms. Radio-activity. Colours of surfaces. Light filters. Production of infra-red rays. Distribution of energy among different wave-lengths.

The Rutherford atomic model

IT is necessary to examine a little more closely the main features of the solar systems of Rutherford. According to the theory which we mentioned at the end of the last chapter the atoms of all elements are systems of planetary negative electric charges, each of which is identical, rotating about a very small and massive central sun, called the nucleus of the atom. This nucleus has a total positive charge which is equal to the total number of negative electric charges in the external orbits. The simplest known atom is, as we might expect, the lightest one, viz. Hydrogen, and Hydrogen atoms behave as if they were made of one electron, or negative charge, circulating in an orbit round a central nucleus containing one positive charge. It is our purpose to try to find out how the electrons circulate in their orbits and the theoretical results of their movements.

First of all, we can picture the motions of the planets in orbits round the nucleus by analogy with the circulation of the Earth round the Sun. To do this we need only replace the gravitational attraction between the Sun and the Earth by the electrical attraction which acts between the positive nuclear charge and the negative charge on the electron. So also, more crudely, we may replace the

string on the end of which we spin a stone by an imaginary attractive force towards our hand. According to classical ideas the rotation of the electron round the nucleus would entail the production of electromagnetic radiation (vide Ch. I, p. 24) of a frequency equal to the frequency of the rotation of the electron in its orbit, but the fact that energy is being given off as radiation would cause an alteration in the speed of rotation (vide Ch. II, p. 58) and the radiation should therefore alter in frequency.

Now if we observe with an instrument containing a prism the light of glowing Hydrogen, enclosed in a tube like those used in electric signs, we notice that the light which comes from the Hydrogen is emitted at a number of different, well-defined frequencies or wave-lengths. Under defined conditions these are fixed and unalterable, are absolutely characteristic of Hydrogen, and are known as 'spectral lines' of Hydrogen. Every element gives its own characteristic wave-lengths and many thousands of these are tabulated in books of reference, so that elements can be identified, even in the most minute quantities, merely by measuring the wave-lengths of the light which they emit and then looking at the tables.

The Balmer Series

Accurate measurements of the light wave-lengths of Hydrogen have been available for many years, but scientists were long at a loss to know why the spectral lines appeared, and they wondered whether there were any simple numerical relations between the wave-lengths of the different lines. One is reminded of the speculation of the last century about the arithmetical relations between the weights of the atoms. It was found that taking, as an instance, one set of six lines in the light emitted by

Hydrogen, the numbers of waves per centimetre* were 15233·22, 20564·79, 23032·54, 24373·06, 25181·34, 25705·96—not a very promising array from the point of view of regularity. Balmer[1] showed, in 1885, that these and many similar figures could be obtained from formulae like the following:

$$\text{Number of waves per centimetre} = 109677{\cdot}7\left\{\frac{1}{n^2} - \frac{1}{m^2}\right\},$$

in which we have only to substitute for n and m the natural numbers 1, 2, 3, &c., in order to derive different sets of figures. To take a particular case, suppose we make $n=2$, and $m=3, 4, 5$, &c. in turn, then the result of some simple multiplication and subtraction gives us the following figures[2]:

Number of waves per centimetre = 15233·17, 20564·77, 23032·54, 24373·06, 25181·35, 25709·97—and it must be admitted that the agreement between these figures and those given above is too extraordinary to be assignable to chance. But we can manipulate the formula indefinitely and get further results, which are also accurate, by putting, for instance,

$n=1$, and $m=2, 3, 4$, &c.
or $n=3$, and $m=4, 5, 6$, &c.
or $n=4$, and $m=5, 6, 7$, &c.

and taking a very slightly different multiplier instead of 109677·7.

We can, of course, convert the 'numbers of waves per centimetre' into wave-lengths by the simple process of inverting the numbers, because the wave-length (in centimetres) is clearly equal to

$$\frac{1}{\text{number of waves per centimetre}}.$$

* There are 2·54 centimetres per inch. Wave-lengths are usually tabulated in metric units, as in Broadcasting.

The corresponding figures[3] are—

Wave-length (in cm.) observed:

$6562 \cdot 80 \times 10^{-8}$ $4861 \cdot 33 \times 10^{-8}$ $4340 \cdot 47 \times 10^{-8}$ $4101 \cdot 74 \times 10^{-8}$
$3970 \cdot 06 \times 10^{-8}$ $3889 \cdot 00 \times 10^{-8}$

Wave-length (in cm.) calculated from the formula:

$6562 \cdot 80 \times 10^{-8}$ $4861 \cdot 38 \times 10^{-8}$ $4340 \cdot 51 \times 10^{-8}$ $4101 \cdot 78 \times 10^{-8}$
$3970 \cdot 11 \times 10^{-8}$ $3889 \cdot 09 \times 10^{-8}$

The agreement between theory and observation is again striking.

We have suggested that we might try the result of inserting different whole numbers for n and m in the formula. The first obvious result is that, if we put $n=1$ and $m=2$, 3, 4, &c., we shall get a series of numbers which are greater than those in the set we have worked out, whereas if we put $n=3$, or 4, and $m=4$, 5, 6, &c., or 5, 6, 7, &c., we shall get smaller numbers. This means, clearly, that the corresponding waves will be shorter or longer, respectively, than those of the Balmer series, which are visible. Thus the series for $n=1$ corresponds to waves which are *invisible* because they are shorter than the waves of ordinary light. They lie in the ultra-violet, and their existence has been confirmed experimentally. Similarly the two series for $n=3$ and $n=4$ correspond to sets of wave-lengths in the infra-red, which are *invisible* because they are too long to be seen. All these waves, beside visible light, are emitted by glowing Hydrogen; they are all in accordance with the predictions of the formula, and they all exist in Nature.

It is difficult to turn from the study of this fascinating picture: we must, however, be content to notice only one more point in which the formula predicts what we ought to observe in Nature. We notice that as we give larger and larger values to m the smaller does $1/m^2$ become, and the

smaller become the differences between the values of succeeding terms of the series. The practical result is that the lines of the spectrum tend to become more crowded together the greater m becomes and to stop dead at a point corresponding to very large values of m.

The upper part of Fig. 6 is a reproduction of a photograph taken by the British Eclipse Expedition at Sumatra in January 1926. Hydrogen exists in the Sun and it so happens that conditions in the Sun's chromosphere favour the production of the lines of the Balmer series. The dark vertical lines represent a number of the members of the Balmer series: the diminution in the distances between the lines as we go towards the left of the photograph is clearly shown and is exactly what our formula tells us they should do. Some lines other than those of the Balmer series appear in the photograph, and the Balmer series actually stops at the point marked 'Head'. Just to the right of this point are crowded together an exceedingly great number of lines which are too weak to show in the photograph, but it is a remarkable fact that the wave-lengths of the first twenty lines of the Balmer series given by Hydrogen in the Sun and glowing Hydrogen in the laboratory have been measured, and that there is the most beautiful agreement between theoretical predictions and both sets of practical results.

Difficulty of explaining the Balmer Series on classical lines

We have noticed already that the wave-lengths of these lines are sharp and do not change as we should expect they would if they were due to the circular motions of electrons which are radiating energy. We have therefore to find some modification of the simple view which will make

intelligible the observed constancy of the wave-lengths of the light emitted by the different elements.

We should be uncommonly surprised if we found that the excursions of a swing could not be made to increase gradually—i.e. that it could be made to swing, say, 1 foot each way and then 2 feet, but not 1 foot 2 inches or any other intermediate figure. According to classical ideas electrons could circulate round a central nucleus in a circular orbit of any radius, because it was assumed that the electron could possess any chosen amount of energy ($\frac{1}{2} mv^2$) and therefore any velocity (v). They were also, it was supposed, capable of absorbing or emitting energy *continuously*; that is, in infinitely small instalments. In 1900, however, Planck[4] astonished the classical school by suggesting, in effect, that an electron cannot circulate in any orbit we like to choose for it, but only in orbits having certain definite radii; or, in other words, the total energy of the atom cannot change by degrees, but only in jumps, or by 'quanta' as the scientist prefers to express it. It is just as if the child's swing were forbidden to swing in the usual sensible fashion and behaved in the odd way described at the beginning of this paragraph.

The Quantum Theory explained

The application of the Planck idea to the Rutherford atom is due to Bohr,[5] who imagined that the electrons could move in Rutherford's orbits *without* radiating energy, but that radiation occurs when an electron suddenly moves from one orbit, in which it has a certain energy, to another in which it has less energy. In the analogy, a swing would not oscillate with gradually decreasing amplitude of movement, but would swing through a fixed distance of 3 feet and then suddenly start swinging through 2 feet.

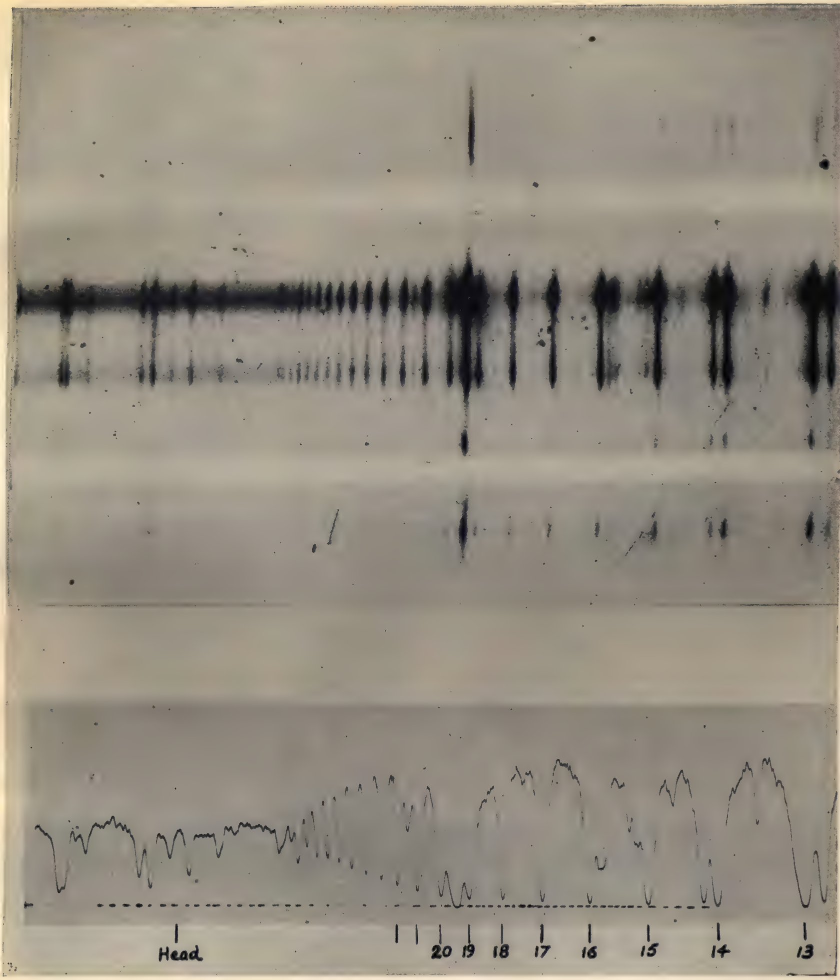

Fig. 6. Balmer series in high prominence and photo-micrometric trace

Of course, the quantum, or jump, idea does not apply to such gross things as swings, but the analogy illustrates the conflict between the classical view 'Natura non facit saltus' and the new quantum view of jumps. As Bacon put it: 'But to a deeper searcher of nature it will plainly appear that nature is accustomed to proceed for some distance by degrees, and then suddenly by jumps, and to take these processes in turn.'[6]

If we apply the quantum idea to the orbits of the electrons, we immediately introduce the discontinuity which is essential if we are to understand how it is possible for rotating electrons to emit light of various constant and different wave-lengths. Bohr says that, when an electron moves from one orbit to another the change of energy is equal to a constant, called Planck's constant (h), multiplied by the frequency of the vibrations of the light emitted.

If we call the initial and final energy contents of an atom E_1 and E_2, we have $E_1 - E_2 = h\nu$,* where h is Planck's constant and ν is the frequency of the emitted light. It is exceptionally easy to work out the frequencies of the light which would be emitted by a model Hydrogen atom built of a single electron, rotating round a central positively charged nucleus, and the answer which the mathematicians give us agrees, in all particulars, with the formula which Balmer obtained by guess-work. We are now much better off because we can calculate,† with a model as the basis of our theory, instead of working with a formula which has no mental picture behind it.

There is no doubt that the mind does not take kindly to the quantum idea—one needs 'a good fancy well pre-

* Greek letter n, pronounced nu.

† The mathematics is given in a simplified form in Appendix II, for the benefit of those who care to follow it.

possessed to help one through'. If the reader finds it difficult to follow the reasoning of the previous paragraphs he may derive some comfort from the knowledge that scientists who had been trained before the acceptance of Planck's theory also found it difficult. The reason for the difficulty may be connected with the fact that we never see anything behaving as the electron does. If we start a motor-car the speed does not change by jumps of 10 miles an hour. The speedometer gradually creeps up, showing that the speed of the car acquires, for an instant, every value from zero up to the maximum.

We shall, owing to the importance of the conception, go through the argument briefly from a slightly different starting-point. Suppose, as Planck affirms, that the energy in light is in some manner divided into small lumps, or quanta, and that the amount of energy in a quantum is $h\nu$. If light of frequency ν is emitted from a radiating atom, say, of Hydrogen, then the energy must be emitted in quanta each containing $h\nu$ units of energy. The loss of a quantum of energy by the atom means that the electron must begin to move in a fresh orbit, such that the difference between the initial and final energies is $h\nu$. The loss of energy occurs instantaneously when the electron disappears from one orbit and reappears in another.

Absorption of energy by an atom may also be looked upon as a discontinuous process, in which the gain of a quantum of energy promotes an electron to another orbit in which its energy is greater by $h\nu$ than it was before.

A Test of the Quantum Principle

One of the most striking confirmations of the quantum theory may be shown by experiments on the absorption of light by certain metals. These experiments may be con-

ducted in small glass bulbs, called Photo-electric cells, which contain a deposit of Potassium and a plate like those in ordinary wireless valves. The plate and the deposit are connected by wires to a battery, the negative terminal of the battery being connected to the Potassium deposit. If the vacuum is good and the glass bulb is in darkness no current flows through the circuit; but immediately light falls upon the Potassium a current starts. This current is proportional to the intensity of the light and is used for very accurate measurements of the candle-power of lamps. A light quantum which falls upon the Potassium is absorbed by an electron of a Potassium atom, which then has more energy than it can hold, so to speak, and leaves the atom altogether. The battery is so arranged to carry the detached electron towards the plate, and there is, accordingly, an electric current in the external circuit.

Now the velocities of the electrons which are emitted from Potassium under these conditions have been measured. It is found that the velocities do not depend upon the intensity of the light, as one would expect, but they do depend most intimately on the colour or wave-length of the light. The actual result obtained is that, if v is the velocity of an electron, then v^2 is found to be proportional to the wave-length of the light. The energy of the electron ($=\frac{1}{2} mv^2$) is therefore also proportional to the wave-length of the light, which is exactly what is predicted by the quantum theory.

The gulf between the Classical and Quantum theories

It would be out of place in this book to give an account of the efforts which are now being made to discover a way of reconciling the two pictures of electromagnetic waves,

given us by the classical wave theory and the quantum theory respectively. In the former theory we had a clear mental picture of waves spreading out uniformly in all directions from a source, and we were able to see that many phenomena, and especially the experiments of Young, could easily be explained by the wave picture. In the quantum theory we are asked to regard electromagnetic energy as existing in the form of small parcels or little bullets, which travel with the velocity of light and contain $h\nu$ units of energy. It is difficult indeed to see how a number of bullets travelling in the same direction could annihilate one another and produce effects which are so easily accounted for by the assumption of waves. It is, however, even more difficult to explain the constancy of the wavelengths of the spectral lines of the elements on the classical theory.

The position at the moment is that, while the classical theory predicts results which are in accordance with experience when we are not dealing with the emission or absorption of waves, we must turn to the quantum theory if we wish to obtain any more information about the manner of the birth of electromagnetic radiation and what happens to it when it is absorbed by any material. The difficulty of understanding how it comes about that the energy which is emitted as a complete quantum, at the instant of a quantum jump, afterwards proceeds as if it were a regular series of waves, extended over a distance and a length of time, cannot be bridged by a mere modification of either theory but involves a radical change in our outlook upon the nature of radiation itself and of the manner in which we interpret our observations. So far as they go both theories are valid in their particular spheres and, so long as we realize their limitations, we are justified

in using both of them until we achieve a more comprehensive theory which will explain both sets of observations in terms of a single conception.

It is not the fault of the scientist that he is unable yet to make the two conflicting views of the nature of light agree. The trouble is that light is neither fish nor flesh. Although we have been in the habit of thinking it was flesh we suddenly had a view which suggested that at least a part of it is fish. A similar contradiction would confront an adventurer who had only been familiar with one aspect of a mermaid.

Returning to the electrical model of the Hydrogen atom, we may insert the correct figures into the symbolical formula which gives us the radius of the Hydrogen orbit. If we do this we obtain a value of about 4×10^{-9} inches. The diameter of the atom is thus about 8×10^{-9} inches, which is not very different from the figure arrived at in Chapter II for the diameter of the Oxygen atom by an entirely different process of reasoning. As a matter of fact all atoms have roughly the same dimensions, because, in the more complicated ones which have many circulating electrons, the attractive force of the concentrated central positive charge tends to shrink all the orbits.

The openwork structure of Matter

Now Rutherford has subjected various kinds of atoms to the action of Alpha-particles derived from Radium, and since these particles, being positively charged, are deflected by the positive charges on any atomic nucleus, it is possible to make use of the results to ascertain the approximate size of the nucleus. The nucleus behaves as if it were very small indeed. The radius of the Hydrogen nucleus is roughly only 1/100,000,000th (10^{-8}) of the

size of the atom itself, so that the inside of an atom is mostly empty, just as the space between the earth and the centre of its orbit (the Sun) is empty. The 'emptiness' of atoms is, however, incomparably greater than the 'emptiness' of the earth's orbit, because the radius of the Sun is roughly 1/400 of the earth's orbit. Electrons are likewise very small things, and although they are bigger than nuclei, their size is only about 1/100,000th of that of the Hydrogen atom.

Ordinary matter, then, is like a mass of bubbles—a good deal to look at but having very little substance. Sir J. H. Jeans[7] says that, if we could concentrate all the parts of a number of atoms—shut up the orbits concertina-wise, as it were—we could pack hundreds of tons of ordinary matter into a pocket-book. This knowledge about the openness of atoms and the relatively vast unoccupied space within them makes it easy to see that X-rays, and all kinds of rays shorter than X-rays, should be able to penetrate large assemblies of them. Their wave-lengths are smaller than the holes in the atom, so that they can easily make their ways through the holes. Light and longer waves are more impeded because they are longer than the X-rays, but even light will go through many layers of thin metal films in such quantity that it is possible to read a book through at least six layers of thin nickel or gold foil. As for the penetration of the Alpha-particles with which Rutherford did his experiments—why, they are only very small positive charges themselves and they go through matter as easily as a charge of No. 5 goes through rabbit-netting. The understanding of these things is only a matter of getting oneself used to a rather unusual point of view, which appears to contradict experience because our senses do not disclose to us the openwork structure of matter.

Having arrived at a picture of the Hydrogen atom which can be made to explain a great number of observations, we wish to see if similar pictures will describe the properties of other elements.

Differences in Atomic Structures

It is noteworthy that, while the mathematics of the Hydrogen atom is simple, there is no mathematical machinery capable of dealing fully with more complex systems of nuclei and electrons. This is unusual because the mathematicians are generally busy forging new tools long before the experimenter can see how to use them. Even a thinker so original as Einstein found a considerable number of his mathematical tools ready and waiting for him to pick them up.

After Hydrogen the next more complicated element on the list is the rare gas, Helium, which can be used by rich countries for filling airships, because though very costly, it is light and uninflammable. The Helium atom consists of a nucleus containing two positive charges, and two planetary electrons. These electrons move in orbits of equal radii but probably not in the same plane. This atom is slightly smaller than the Hydrogen atom because the nucleus has a double charge and therefore attracts the electrons more strongly.

If we add another positive charge to the nucleus and put another countervailing electron among the planets, the added electron does not interfere with either of the previous two, but takes a solitary course outside them. The name of the corresponding element is Lithium. It is a light metal very like Sodium in its properties, and is one of a set of elements, Lithium, Sodium, Potassium, Rubi-

dium, and Caesium, which all bear strong family resemblances to each other.

Fig. 7 shows diagrammatically the internal structure of the atoms of Hydrogen, Helium, and Lithium. The small central dots represent the nuclei and the small circles the electrons. The dotted lines are intended to indicate the tracks of the electrons round the nuclei. The scale of these diagrams is given roughly by the line *AB*, which represents a length of 1/400,000,000th of an inch.

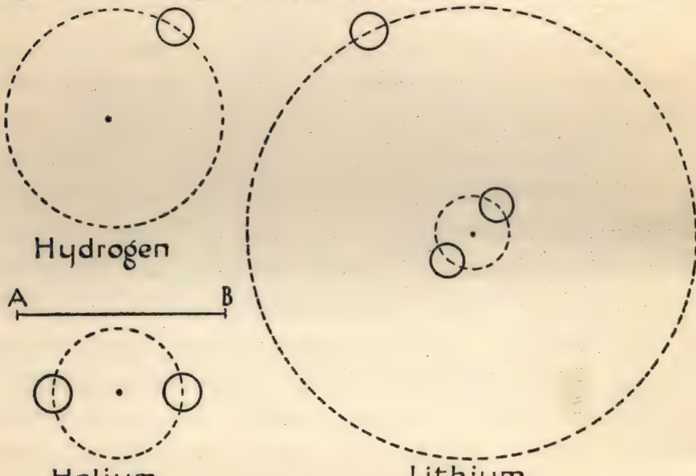

Fig. 7. Shows diagrammatically the internal structure of atoms of the elements Hydrogen, Helium, and Lithium

The addition of further positive charges increases the weight of the atom because each positive charge is associated with a constant mass, while the addition of electrons increases the complexity of the orbits round the nucleus. Further electrons, after the number of 3, take up their positions in the outer system of the Lithium atom, until we arrive at a structure consisting essentially of a nucleus having 10 positive charges, an inner set of 2 electrons, and an outer set of 8 electrons. This element is Neon—

another rare gas which closely resembles Helium in all its properties.

To go from Neon to the next heavier and more complicated atom, Sodium, we add one positive charge to the nucleus and another electron to the gyrating assembly. This additional electron does not join the outer shell of 8 electrons of the Neon atom but takes an external course of its own, outside all the others. This system then resembles Lithium in having one electron more isolated than the others, and this is the reason for the resemblance between Lithium, Sodium, Potassium, and the other members of the family. The addition of more negative charges to the outer shell can continue until we have built another complete ring of 8 electrons (Argon), but after Argon the next heavier atom again has a single external electron and the corresponding element is Potassium. The periodicity of the properties of the first twenty elements, which was observed by Mendeléeff and others, is due to the tendency of the electrons to group themselves in rings or shells surrounding the nucleus and containing not more than 8 electrons per shell. The family resemblances between elements are due to the identity of the numbers of electrons in the outermost shells rotating about different inner structures.

We can make a list of the chemical elements showing the names, atomic weights, numbers of positive charges on the nuclei and the numbers of electrons which rotate in the different shells surrounding the nucleus, and when we do this we find that, in the more complicated and heavier atoms, there is a tendency to form outer rings of 18 and then of 36 electrons,* instead of only 8. The chemical and

* It is significant that the numbers of electrons in the shells surrounding the nucleus of an atom are 2, 8, 18, 36—i.e. 2×1^2, 2×2^2, 2×3^2, 2×4^2.

physical behaviour of even the very complex atoms depends nevertheless in the main upon the number of electrons in the outer ring.

Let us imagine an element in which the electrons are arranged so that any added electron must go into an inner ring and not into the outer one. If, to an atom of this kind, we add a positive charge to the nucleus and an electron to the circulating cloud of negative charges, then the resulting element will resemble the first because the outer electrons have not been interfered with, while the atomic weights will be different, but nearly the same. This is one of Mendeléeff's observations which our electrical model explains. Generally speaking, the properties of the chemical atoms are in accordance with theoretical predictions which can be made from a study of our models, and the difficulties which were found by Mendeléeff in fitting certain elements into their proper order have been explained by the electrical theory and thus our trust in the model—'a mere anatomy' though it be—has been strengthened.

In the foregoing paragraphs we have shown how satisfactory model atoms may be constructed out of electricity, and we have attached great importance to the number of positive charges on the nucleus, which decides the mass and other properties of the atoms. We must notice that the nuclei of atoms contain negative as well as positive charges but that the positive charges are always in excess, and it is the number of the excess of positive charges over the negative which determines the number of electrons in the outer orbits. If this were not so, we should have difficulty in explaining how it is that the atom of Helium, which is about four times as heavy as the Hydrogen atom, has a nuclear charge of two units while the

Hydrogen nucleus has one charge. Since the mass of an atom depends mainly on the number of positive charges in the nucleus, the ratio of the weights would be two to one if there were only positive charges in the nuclei. As things are, however, the Helium nucleus consists of four positive charges and two negative charges, making the mass four times that of Hydrogen and the net charge only double.

Formation of Chemical Compounds

Besides giving an explanation of the optical and chemical properties of atoms, the Rutherford model shows us why different compounds occur and not others. If we consider the atoms of Hydrogen and Chlorine, we find that Hydrogen, has one circulating electron and Chlorine seven in the outermost orbit. The tendency of electrons to form rings or shells of eight electrons leads us to expect that, when these two gases are mixed, the outer Chlorine ring will appropriate the single Hydrogen electron, and the Hydrogen atom, being then positively charged instead of neutral, will be bound to the Chlorine atom, which has acquired an additional negative charge, by the consequent electrical attraction. The Oxygen atom has only six electrons in its outer ring. It needs two to make eight, and therefore we have to supply two Hydrogen atoms to satisfy the requirements of one Oxygen atom. This is in agreement with the result of chemical analysis of water (H_2O), which tells us that there are two atoms of Hydrogen and one of Oxygen in each molecule of water.

The picture of the atoms of compounds bound together by electrical forces makes it easy to understand the reason for Faraday's observation of the constant relation between the quantity of electricity and the weight of a metal or

other substance deposited by it on the plates of his apparatus.

Suppose we admit the possibility that a molecule of Hydrochloric Acid (HCl) is, when dissolved in water, a less stable structure than it appears to be when it exists in the gaseous form. If there is any loosening of the electrical bonds between the atoms, then there are in the solution numbers of pairs of H atoms and Cl atoms each bearing an electric charge, the one (H) positive and the other (Cl) negative. These charged atoms will be forced in opposite directions by the electrical pressure between the plates in Faraday's experiments, and will eventually arrive at the opposite plates where they are deposited and surrender there the appropriate charges.

Radio-active Substances

According to our theory, the radio-active element Uranium has a nucleus with ninety-two positive charges and an 'atmosphere' of ninety-two electrons whirling round it. It is no wonder that this element and others which are nearly as complicated are never inactive. What appears to be happening is this. The nuclei of these elements are far from being simple coherent units which are incapable of subdivision. They are in fact so highly organized that their organization cannot stop breaking down spontaneously and it usually begins to disintegrate by shooting out a portion of its nuclear charge in the form of an Alpha-particle. It also shows its desire to be rid of some of its concentrated energy by emitting at intervals Beta-particles and Gamma-rays. All these properties of radio-active substances are due to the disruption of the over-complicated nucleus, and since the nucleus is the soul of the atom—the ruling spirit of its being—explosions

in the nucleus will change the character of the atom. This is in agreement with observation, for that very harmless material, lead, is an end-product of a series of radio-active transformations lasting millions of years. Radio-activity is then only a name for the extraordinary effects which accompany the transmutation of elements under forces of unearthly intensity over which we cannot exert the slightest control.

Transmutation of Elements

Having seen that the elements are different arrangements of positive and negative electricity and that some elements spontaneously turn into others, we may ask ourselves whether we are any nearer to the attainment of the dream of generations—the artificial production of Gold. All we need do to attain this object is to arrange electric charges so that they are in the proper numbers and have the same energies and orbits that they have in the natural Gold atom. If we wish to transmute elements, we must first of all attack the nucleus which is at the root of the internal affairs of atoms, and the only satisfactory means we have of doing this is by using the high-speed Alpha-particles which are shot out by Radium as projectiles wherewith to attack the stronghold. No form of ordinary physical violence will hurt an atom or disarrange its structure, but an Alpha-particle is capable of disrupting the nucleus of an atom when it hits it. Rutherford has shown that Hydrogen can, by this means, be 'knocked out' of Nitrogen, Sodium, Phosphorus, and many other elements; but transmutation on commercial lines is at present unthinkable owing to the enormous amount of energy required to effect the decomposition of a single atom. One can easily see that an atom is a sufficiently small

target for an Alpha-particle to hit, and when one remembers that the nucleus is far more minute than an atom which is mostly emptiness, it is not surprising that out of about ten thousand million collisions between Alpha-particles and Nitrogen atoms only one is effective in breaking down the nucleus.

The tracks of Alpha-particles through gases have been studied with the assistance of an ingenious instrument which makes it possible to see or photograph the route along which an individual particle has passed. The particle is made to leave behind it a trail which may be likened to the trail of smoke left in the sky by an aeroplane which is writing sky-signs, with the difference that the visible track of the particle is due to its passing effect on the molecules of the gases in which it is travelling and not to anything emitted by the particle. Fig. 8 is a photograph showing the tracks of Alpha-particles emitted by a small quantity of a radio-active material: the 'hairs' of the 'shaving brush' are each tracks of single Alpha-particles, and it will be seen that, with the exception of two or three, the range of all the particles is about the same. Fig. 9, which is a reproduction of another photograph taken by the same method, shows some more tracks of Alpha-particles. The interesting points about this picture are the kinks which can be clearly seen near the ends of two of the tracks. Each of these kinks is the result of the near approach of the particle which made the track to the nucleus of one of the gas atoms among which the particle was moving. The course of the particle is changed in a manner which is not unlike the effect of a collision between two billiard balls, the actual change, however, being the result of the electrical repulsion which exists between the positively charged Alpha-particle and the positively charged nucleus.

Fig. 8. Tracks of Alpha-particles from a radio-active substance

Fig. 9. Tracks of Alpha-particles showing kinks due to near approach to atomic nuclei

There is no mystery about the operations by which the modern alchemist performs his transmutations. They can be repeated by any one who will read published accounts of the work, and they are the logical development of the electrical theory of matter. In the old days alchemists disappeared behind a smoke-cloud of words when they appeared to be on the point of announcing a discovery, or they pretended that their mysteries were not for the crowd. 'I could say more than this, but I must be silent. If it were not diametrically to oppose the will of God, it would be the easiest thing possible to make all rich alike by a very few words, and to fulfil the wishes of everybody.'[8]

The Relation between the Emission and Absorption of Light

In the preceding discussion of the origin of electric waves it has been shown that the movements of electrons from one orbit to another can be made to account for emission of numbers of waves of different lengths by atoms which are 'excited' either by heat or by electrical discharge. Atoms similarly absorb light of definite wavelengths and are unaffected by waves which they cannot produce themselves, just as a resounding body will not respond to a vibration which is not of the appropriate frequency.

We are able to discriminate between paints of different colours because some of the white light which falls upon them is absorbed; the remainder is reflected, and it is this portion of the original sunlight which we describe as the colour of the paint.

A white surface appears white only when illuminated with white light, and a coloured surface shows its true colour only in white light or in light of its own colour.

A red surface appears red in red light but almost black in green or blue, the reason being that the green and blue rays are absorbed by the red surface and very little light reaches the eye. Some striking stage effects, in which the scenery and dresses appear to change colour instantaneously and things which were invisible become visible, are brought about by an intelligent choice of colour-schemes and appropriate changes in the colour of the stage lighting. In some theatres there are arrangements for illuminating the stage, or a particular part of it, with light from any part of the spectrum, so that many colour-changes are possible with only one setting. The effects of colour filters and coloured surfaces in altering the quality of the original illumination are all due to definite relationships between the frequencies of waves present in the original light and frequencies of the vibrations which the particles in the filters or paints can execute under the influence of the electrical forces in the waves. In other words, these particles are capable of picking out certain frequencies and of behaving like a number of tuned violin strings which will pick out and respond to definite notes in a heterogeneous mixture of sounds.

The absorption of energy by any 'tuned' system depends, of course, upon resonance. The radical principles of 'selective' light absorption are similar to those underlying the acoustic experiments described by Morhof, and analogies are found in all branches of science when we have to deal with waves and with things which vibrate at definite rates. Even in wireless broadcasting there is a notable loss of strength of signals which travel over a suburban area where there are many receiving sets tuned to the frequency of the local station. These sets, being capable of responding to a particular frequency, can

abstract a large amount of energy from the waves which pass over them. Incorrectly tuned sets receive nothing and the waves go by without losing strength.

We know from experience that a dead black rough surface absorbs nearly all the light which falls upon it, and measurements show that it absorbs also the infra-red rays. This is why light-coloured clothes are popular in summer and in the Tropics. A hot black surface emits radiation over a large range of wave-lengths, just as it absorbs almost completely over a similar range. The amount of energy which a hot black plate emits *at a particular wave-length* depends upon the temperature; that this is so is easily realized, because the top of a stove can be felt to radiate energy long before it is hot enough to see. As it gets hotter it glows red, yellow, and then white, and we are accustomed to speak of things being red, yellow, and white hot, which implies a realization that the colours are related to the temperature of the hot body.

The Origin of Infra-red Rays

In considering the origin of infra-red rays we remember, first of all, that the energy of a hot body resides in the vibrations of its parts, and we must learn something about the amounts of energy in the different vibrations before we can predict anything about the way it will be radiated from a hot surface. It is helpful, before dealing with the infra-red radiation, to return to the mechanical picture at which we arrived in Chapter II when discussing the movements of gas molecules. We saw that we could calculate, among other things, the average velocities of a swarm of similar molecules on the assumption that their movements are at random and that there is no reason why one molecule should behave differently from others.

It will be apparent that, if we have a large number of molecules colliding with each other in a state of chaos, then there will be instants when some molecules will have undergone a series of impacts tending to reduce their velocities, while others may have been 'pushed from behind' so that they are travelling with velocities greater than the average. The point is that, while the average velocity of all the molecules is unaffected by these random collisions, there will always be a few travelling far faster than the average and a few going much more slowly, or even stopped altogether, at any instant. The actual numbers of gas molecules travelling at different speeds can be determined mathematically and the formula which we deduce states in an accurate form the general conclusion at which we have just arrived by common-sense reasoning. We can express the same result by saying that, while the average *energy* of all the molecules is constant, there are, at any instant, some molecules having little or no energy, while others have much energy and correspondingly great velocities. The majority have velocities and amounts of energy which differ little from the average.

We have been speaking of the velocities of a number of gas molecules and of the energies associated with them. Since we shall have to deal with energy associated with vibrating particles, it is important to realize that we can look upon the motions of gas molecules as the result of numbers of complex vibrations and the energies as being associated with these vibrations. The vibrations may be likened to a number of receptacles capable of holding energy, and we may form a rough picture of the way energy divides itself among the various possible vibrations by considering what would happen if we distributed a great number of grains of sand at random among a

number of small boxes. We can easily see that boxes with no sand in them, or full boxes, would be few, but that most of them would contain very nearly an 'average' amount of sand. So, also, with the vibrations of the particles of a hot body—most of them have amounts of energy which are not far removed from a certain mean value. The same sort of thing is common in Nature. We see millions of men of ordinary height, ordinary intelligence, and having ordinary faces. Extremely tall or very short people are the exception; the vast majority are average specimens and great variations from the mean are rare.

Our mechanical analogy has given us an idea of the state of things inside a volume of gas, and we have observed that no one molecule is favoured above the others. It would be better to say that 'no one molecular motion is favoured' above others, for it is the motions (whether regarded as velocities or vibrations) which share the available energy. We can make this point clearer by considering what happens to a pendulum swinging in air in a closed box. We know that the pendulum will eventually stop swinging because its energy goes into random vibrations in the air: each molecule, being capable of a certain number of motions—e.g. to and fro, left and right, up and down—demands for every motion an equal share of the total energy available in the box, and greedy hands are laid upon the pendulum which has initially a large amount of energy all in one to-and-fro vibration. The process goes on until the energy of the pendulum has been divided among all the molecules and the pendulum is left with insufficient energy to allow it any appreciable motion.

This is a model of the Ideal Socialist State, in which mediocrity is glorified and all men are entitled to an equivalent share of whatever is available. But there is a

moral in the model. For if we will ask wise Nature a closer question, we shall find that she does not deny the existence of very large or very small quota of energy, but she ensures that the number of large or small quota shall be negligible compared with the number which differ little from the average.

Now we know that the energy of a hot body exists in the form of vibrations of its parts: each motion of every particle in a hot body being capable of holding some energy, it follows that the total energy of a hot body is related to the number of particles in it as well as to the number of motions which each particle is free to execute. Since the parts are held together, according to the electrical theory of the structure of matter, by electrical attractions between the atoms and molecules, any agitation of the parts is bound to give rise to alterations in these electrical forces and hence to the radiation of electromagnetic waves in the surrounding ether, which is capable of transmitting all electrical vibrations equally well.

The number of particles in a cubic inch of any ordinary material is large but by no means immeasurably great. If we imagine a series of substances which are progressively more finely divided, we can say at once that, other things being equal, the most finely divided substance will be capable of holding a greater amount of energy than those which are coarser. Following this line of reasoning, we have no difficulty in seeing that a medium which could be infinitely subdivided would be able to hold an infinite amount of energy because the number of possible vibrations of its parts would be infinite. Since we have learnt to look upon the ether as a *continuous* medium—i.e. we cannot, by any amount of subdivision, arrive at a point at which no further splitting is imaginable—we deduce that

a cubic inch of ether is capable of holding an infinite amount of energy. And remembering that the whole vast volume of the ether is waiting to absorb the energy (radiated as electromagnetic waves) of a hot body, we come to the absurd conclusion that, if the energy of a hot body is to be distributed indiscriminately among the vibrations of its parts and all the possible vibrations of the ether, then almost all the energy of the hot body would go into ether vibrations and the hot body would be left cold. Similarly human life would be impossible on the earth because all terrestrial energy would quickly be drained away by the ether and everything would freeze.

The Distribution of Energy according to Wave-length

This difficulty is one of many which disappear when we adopt the views of Planck. He sets out with the idea, outlined above, that a hot body consists of a vast number of little structures, or 'oscillators', which are capable of vibrating at different fixed frequencies, but he adds the proviso that they can absorb or emit energy only in multiples of a certain definite quantity which is fixed for each structure. If one of these little 'oscillators' has a frequency of vibration ν, then, according to the quantum theory, it can emit energy only in multiples of $h\nu$ and the amount of energy radiated by a hot body at any particular frequency will depend upon the numbers of oscillators which are full of energy and ready to part with it. We may suppose that part of the energy of the vibrations is acquired by the mutual jostling of neighbouring atoms and molecules, and that some of the energy which is divided among the oscillators in this way appears as radiation. If we concentrate our attention upon a number of oscillators for which ν is large, it is clear that, since they must be given

large amounts of energy before they can disgorge any, they stand a poorer chance of being in a position to radiate than those oscillators which do not demand such a large amount. This suggests that the amount of radiation will be small at very high frequencies and will be greater at moderate frequencies. We can also see that the low frequency vibrations will more easily acquire their small quanta but that, owing to their low energy, they will probably radiate less strongly than certain vibrations of higher frequency.

The idea underlying the theory of the production of radiation by the effects of impacts between the parts of a solid body is brought home to one by reconsidering the effect of hammer blows on the head of a nail (see p. 54). When the head of a nail is hammered the atoms and molecules are shaken and acquire energy. Some of this energy is divided among the 'oscillators' which are able to radiate when they have received a sufficient quantity of energy. If there is little energy only those oscillators which require a small quantum will be excited and the radiation will be limited to the very long infra-red rays (small quanta), but if the hammering is violent sufficient energy may be supplied to excite the radiation of the short-wave oscillators (large quanta), and the nail-head will glow with a dull red colour. It is, in practice, easier to supply energy to a piece of metal by passing an electric current through it than by hammering it. A small current flowing through the filament of an electric lamp will produce no visible radiation, but the filament will turn red and then white as the current increases. As more and more energy is made available oscillators requiring larger and larger quanta are able to obtain enough energy to excite them and shorter and shorter waves are produced.

We can obtain a direct confirmation of the usefulness of our assumptions by measuring the amount of energy emitted by a hot body at different wave-lengths. We find that very little energy comes out in the form of very short or very long waves, but that there is always an intermediate wave-length at which the energy emission is a maximum. This, if we like so to regard it, shows a desire of Nature not to allow extremes of any kind to predominate. Looked at from the point of view of Planck, it means that the available energy divides itself among all the possible vibrations of a hot body so that the very high and the very low frequencies have little energy, while most of them have amounts of energy which do not differ greatly from a certain mean.

Using Planck's hypotheses of the discontinuity of energy and its unequal division among the vibrations, it is possible to calculate the energy which is emitted by a hot body* at any one temperature and at any particular wave-length. We evolve a formula which shows that we must expect a maximum intensity of radiation at a particular definite wave-length (which is different for each temperature) and a gradually decreasing intensity at longer or shorter wave-lengths. This is in full agreement with what we observe when we measure the energy emission of a hot body. If our hot body is only warm the wave-length corresponding to the point of maximum energy emission is in the infra-red and too little visible light comes from it for us to see. At 500° Centigrade a hot body is just visible, but the maximum emission is still in the invisible region.

* The term 'hot body' is used here instead of 'black body'—a term which has a special significance in Planck's theory. The theoretically ideal 'black body' which would behave *exactly* as theory indicates does not exist in Nature, but close approximations to it can be devised.

Dull red, orange, and white heat correspond to temperatures of roughly 700, 1100, and 1300–1500° Centigrade, and as the light emitted becomes more intense, so does the wave-length at which the energy emission is a maximum decrease. Planck's theory also explains why bodies do not surrender all, or nearly all, their energy to the ether. Although the ether is able to vibrate in an infinite number of ways and is thus capable of holding an infinite amount of energy, it is not given a chance to absorb all the energy of the universe because the energy of material bodies is unequally divided among the various possible vibrations. The high frequency ether vibrations which would absorb most of the energy of hot bodies, if it were infinitely divisible, cannot abstract any considerable quantity from them simply because the necessary quanta do not exist in large numbers.

Except at very high temperatures the maximum energy emission occurs at wave-lengths which lie in the infra-red region, and special instruments have been designed to detect and measure the amount of these radiations. Having seen how we may explain to ourselves the origin of these waves, we propose in the next chapter to describe some of the sensitive instruments which have been evolved for use in the infra-red range of wave-lengths.

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IV

DETECTION OF INFRA-RED RAYS

Direct sensation. Colour changes. Photography. Expansion of materials. Thermo-junctions. Electrical resistance changes. Radio-micrometers. Radiometers. Use of phosphorescent substances.

Sources of Infra-red Rays

STRICTLY speaking, everything we see around us is always radiating and absorbing electromagnetic waves. The loss of energy by a hot body is due, in ordinary circumstances, partly to loss by radiation, which will of course take place in a vacuum as well as in air, and partly to the direct energy loss due to the increased movements of the air molecules which touch the heated surface of the body. This latter energy loss does not occur when the hot body is in a vacuum, and this is why the contents of a vacuum ('Thermos') flask retain their heat longer than those of an ordinary bottle.

We should find that a hot-water radiator would be an ineffective means of warming a room if it were filled with ice-cold water. This is because the surface of the radiator would absorb more energy than it emits. If the room temperature were $-40°$ the ice-cold water would warm the room because it would then emit more heat than it could absorb.

Thus, although all surfaces are radiating and absorbing heat continuously, we count as 'hot' only those bodies which radiate considerably more heat than they absorb, and we regard them as sources of heat. The temperature of a hot body, relative to its surroundings, determines the amount of heat it will emit in one way or another in a given time, and it is also, as we have seen, the deciding factor

in fixing the wave-lengths of the electromagnetic (heat and light) waves which are emitted.

We do not regard a body as really hot until it is hot enough to be a possible source of discomfort if we touch it, and we can use the same criterion of hotness when we are looking for sources of infra-red rays. No body which is not hot according to this criterion can radiate very much energy in the infra-red region. It is, indeed, impossible to produce a powerful source of infra-red rays without using a source which is very hot indeed—i.e. it has reached a temperature at which it radiates light as well as heat.

In spite of this we can make many experiments with infra-red rays by using, as a source of the rays, nothing more elaborate than a warm metal ball which is at a temperature far too low to be visible even in the dark. We can feel the heat radiated from such a hot ball and the escape of heat will not be stopped if we suspend the ball in a vacuum chamber having walls which allow heat rays to pass through. The infra-red rays emitted by our hot ball behave, except for their invisibility, in many ways like light rays. We know that a motor-car headlight projects a beam of light in front of a car. If we take the bulb out of the lamp and put a warm metal ball in its place, we project, instead of a beam of light, a beam of infra-red rays. We can detect the rays, when they fall upon us, by the sensation of warmth they produce, and this is the only way in which we can become directly aware of heat radiation.

Since we are unable to produce, an intense source of infra-red rays without raising the temperature of the source above that point at which visible radiation is produced as well as infra-red, it is necessary, when we wish to employ only the infra-red rays, to remove the visible radiation from the total radiation of the source. We know that we can

easily produce coloured beams of light by putting pieces of coloured glass in front of a white light: the glasses remove from the mixture of rays in the white light all except a limited number which they transmit. The beam which comes through the glass is coloured because certain rays of the original mixture which make what we call white light are missing in the coloured beam.

Taking any hot body, say a white-hot steel ball or an electric arc, we can filter out the visible and retain the invisible rays by putting, in front of the source, the equivalent of a piece of coloured glass. There are many substances which allow the infra-red rays to pass through and yet stop all light, but the most common and convenient filters are made either of glass containing oxides of Iron and Manganese, thin sheets of ebonite, solutions of certain substances, and gelatine films impregnated with dyes. If a properly made screen of any of these materials is placed in front of a fire it stops all the light and yet lets through the heat. It will be noticed, on the other hand, that an ordinary glass fire-screen stops a great deal of the heat and lets through most of the visible radiation. Between these two extremes we have a large choice of filters. The action of infra-red filters is essentially similar to that of ordinary colour filters except that the radiation passed by the filter is invisible. The compositions of infra-red screens are chosen so that no vibrations can be transmitted except invisible ones: the visible are entrapped and held within the filter itself, just as all but red rays are taken out of white light by a piece of red glass. It is quite easy to demonstrate the presence of the heat rays which pass through a filter when the source is intense. The rays may, for instance, be concentrated with a lens on some inflammable substance which will then burst into flame.

There is, of course, no prior visible indication that anything is passing between the filter and the focus of the lens.

Detection of Infra-red Rays

The skin is far too insensitive to be useful in any investigation of the invisible rays. We must therefore devise instruments which will be effective in the region of the electromagnetic waves with which we are dealing and to supplement our senses, where they fail us, by transforming the energy of the infra-red rays into something which we can detect more readily. Users of wireless sets will find no difficulty in accepting this idea, for the invisible and inaudible electromagnetic waves sent out by Broadcasting Stations are transformed by a receiving set into sounds which are heard in the telephones. We are similarly able to change the energy of the infra-red rays into electric currents which may be made to produce a visible movement, or we may turn it into sounds.

Detection by Colour Changes of Special Substances

There are a few peculiar substances which can be used as direct indicators of sufficiently intense heat rays because they change their colour when heated. One such substance is a compound containing the iodides of Mercury and Silver. It is a pale yellow until gently warmed and then it changes to a brilliant red. The process by which this colour change comes about is still obscure, and it is intensely interesting to watch an individual yellow speck while it is being warmed and to speculate about what is going on inside it. Often the speck can be seen to go red in one small corner and then nothing happens until the whole of the speck suddenly changes colour just as if an infection had spread over it. We do not rely upon any

effect like this in practical work with invisible radiation because no one has yet shown how to make crystals which will respond to exceedingly small quantities of heat.

Detection by Photography

Ordinary photographic plates are less sensitive to the longer waves of the visible spectrum than they are to the violet rays, and this is why red objects appear very dark or black in a photograph and why a deep red light is used in photographic dark rooms. Commercial plates are almost unaffected by infra-red rays, but may be made sensitive to them by the addition of certain chemicals to the emulsion. Some fifty years ago it was shown to be possible to photograph a kettle of hot water in a dark room using a plate treated in this way. Further reference to the uses of special plates will be made in Chapter V.

The remarkable photograph reproduced in Fig. 10 brings home to us the resemblance between infra-red rays and ordinary light rays, and it is perhaps difficult to believe that it was taken in total darkness. The objects shown, a brown glass bottle, the tin cover of a can of photographic chemicals, and a clear glass measuring cylinder, were exposed to the infra-red rays coming from an electric stove which was supplied with so little current that the heating elements remained invisible. The heat of the stove was focused on the objects by metal reflectors, and a camera containing a specially sensitized plate was focused on the objects and given a long exposure. The resulting picture, which the author believes to be unique, represents what we should have been able to see in the dark room if the sensitiveness of our eyes extended outside the small range of wave-lengths in which they are effective.

Fig. 10. Photograph taken in total darkness

Fig. 11. Galvanometer and thermopile, with lamp and scale, ready for detecting heat radiation

Detection by Expansion of Materials

Metals and most other substances expand under the influence of heat, and this is why gaps are left between the ends of consecutive rails on railway and tramcar tracks; were there no gaps the rails would warp when the temperature rose. The expansion of a short length of metal is very small, but it can be made visible by the use of a magnifying lever or by other methods. If two strips of different metals which expand differently on heating are riveted together, the compound strip will bend when heated because one side expands more than the other. The movement of one end of such a bimetallic strip can be made to move a pointer over a scale and thus indicate the temperature of the strip directly. Similar strips are used in the manufacture of balance-wheels for watches and clocks. The bending of the strip is here used to annul the effects of temperature changes upon the rate of the clock or watch. In spite of the possibility of magnifying the expansion of metals it is not practicable to measure extremely small quantities of radiant heat with instruments based on this phenomenon.

Another obvious way of detecting the infra-red rays is to use the expansion of liquids to make visible their heating effect. The mercury rises in the stem of a thermometer when it is exposed to the heat of a fire, and this instrument was most commonly used in the early days of last century. More delicate detectors of heat radiation can be made by using a gas, instead of mercury, as the expanding substance. For this purpose the gas (air, Hydrogen, &c.) is enclosed in a blackened glass bulb connected to a fine bore tube containing a pellet of mercury or a coloured liquid. When heat falls on the bulb the expansion of the

gas inside moves the pellet along the tube, and the amount of heat which has been absorbed by the blackened surface is indicated by the extent of the movement of the pellet. These instruments have their uses, but, on account of the comparatively large amounts of heat required to affect them, they are generally insensitive.

Detection by Thermo-junctions

It happens that the most sensitive instruments which are available for detecting small quantities of radiant heat demand the use of delicate electrical measuring instruments called galvanometers. These are refined forms of the small ammeters which are fitted on the instrument-boards of motor-cars. In ordinary ammeters the magnetic force due to an electric current moves the pointer of the instrument against the recoil force of a small spiral spring, but in the more sensitive forms of galvanometer the current goes through a small coil of wire suspended on a very fine thread made of quartz or metal, so that the torsion of the thread is opposed to the magnetic force. The movements of the coil are made visible by the motion of a spot of light which is reflected from a minute mirror attached to the coil. The reflected beam of light replaces the pointers which are fitted on less sensitive current detectors, and it is easily seen that a very minute movement of the galvanometer mirror will cause an appreciable motion of the spot of reflected light. This may be demonstrated by watching a spot of light thrown upon a wall by a hand mirror. It is almost impossible, holding the mirror in one's hand, to keep the spot still. The slightest shaking of the hand, or any other movement, appears as a greatly magnified displacement of the spot.

If we solder together the ends of two pieces of wire of

different metals and put the joint into hot water, or in a fire, an electric current flows through the joint from one metal to the other. The joint, in fact, behaves itself like a very weak battery and the current from it may be detected by connecting the two free ends of the wires to a galvanometer. The greater the temperature of the joint, the greater will be the deflexion of the spot of light reflected from the small mirror attached to the coil of the instrument. The metal junctions which are used in this way for the detection of radiation are known as thermo-couples or thermo-junctions, and they are in general use in industry for measuring and controlling the temperatures of furnaces.

Recently a great deal of research has been done on the properties of pairs of substances which can be used as detectors of heat. Many combinations of metals for making thermo-junctions have been tried, as well as of metals and certain natural crystals which generate electric currents when heated. The result of this work and of improved methods of constructing the junctions has been to increase the sensitiveness and reduce the time of response of these elements. In some modern types of thermal detectors the whole unit is enclosed within an evacuated glass or quartz bulb, with a small mirror or a tiny blackened plate for concentrating as much energy as possible upon the junction. The bulbs containing the heat detector are generally about the size of a small wireless valve.

The photograph (Fig. 11) shows, on the left, a modern type of galvanometer connected to a group of thermo-junctions (in case) and the lamp which throws a beam of light upon the little moving mirror inside the instrument. The reflected spot of light moves along the

horizontal scale above the lamp and indicates the amount of heat which falls on the thermo-junctions.

Detection by Bolometers

It is well known that electricity does not flow equally easily through all materials. When we connect the terminals of a battery by a length of copper wire and measure the current, we see that the amount of current which flows is greater than it is when the copper wire is replaced by an equal length of iron wire of the same diameter. But it is less generally known that the resistance of many materials to the passage of electricity increases if we heat them. This phenomenon gives us the clue to another way of detecting radiant heat, in which an exceedingly thin strip of blackened metal is exposed to the heat rays. A small electric current produced by a battery passes through the strip and a galvanometer. When heat falls upon the strip the electric current will be more or less impeded according to the intensity of the heat, and the galvanometer will indicate these variations by the movements of its light spot. Instruments which depend upon this principle are called bolometers, and the metal strips are usually made of blackened platinum foil less than one ten-thousandth of an inch thick.

A portable bolometer outfit which is used for the direct measurement of the radiation from furnaces, &c., is shown in Fig. 12. The blackened face of the heat-sensitive element is seen in its container on the right of the picture, while the needle of the instrument on the left shows directly the amount of heat which is affecting the sensitive element at any moment.

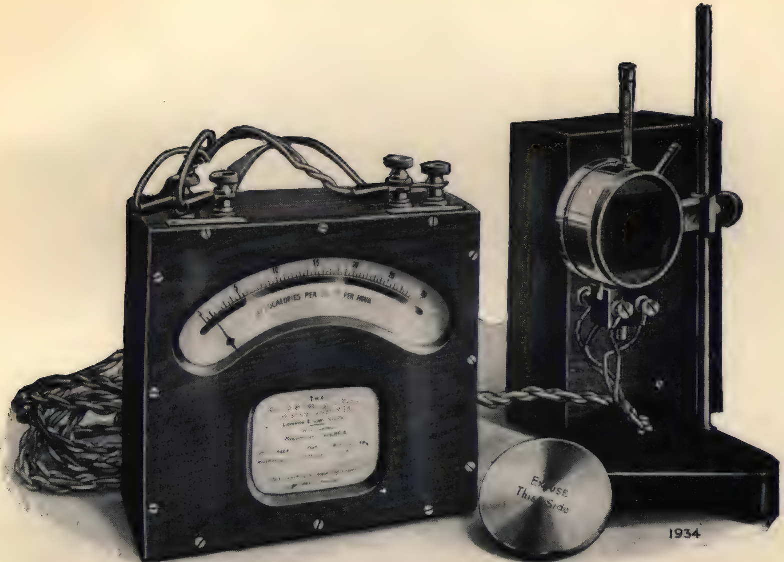

Fig. 12. Portable bolometer outfit for measuring heat radiation

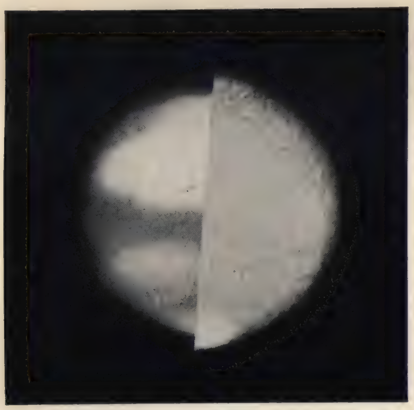

Fig. 13. Mars. Left half taken on a special plate and right half on an ordinary plate

Detection by heat-sensitive Substances

Investigations of substances whose resistance changes under the influence of heat have produced materials which show much larger changes, for the same amount of heat, than ordinary metals. It has been known, for instance, for a long time that the element Selenium* has the property of developing very large changes in its resistance to an electric current when exposed to light. If one watches the needle of an ammeter (or, better, the spot of light of a galvanometer) which is connected in a circuit containing a battery and a specimen of Selenium, the ammeter shows that more and more current flows the brighter the light in the room. It indicates directly the switching on or off of electric lamps, and this strange property has been employed in lighting systems to switch on street lamps automatically when the light fails at dusk or owing to a sudden fog.

Research-workers have discovered that it is possible to produce artificially substances which have properties similar to those of Selenium but which are most sensitive to the influence of the invisible infra-red rays. One of these substances is called 'Thalofide' and it contains the elements Thallium† and Sulphur in combination. This material is sold in glass tubes fitted with terminals for attaching to the galvanometer and battery, and when the apparatus is connected, the galvanometer records the fluctuations in the amount of heat falling on the Thalofide Cell. It will, for instance, indicate the passage of a person between it and the fire because the heat of the fire is cut off momentarily. If there is no fire it will still detect his arrival

* Selenium is a greyish metal. It was discovered in 1817 and occurs naturally in cavities in Vesuvian lavas.

† Thallium is a very soft bluish-white metal resembling Lead. It was discovered in 1861.

into its field of 'view' on account of the heat radiated from his body, especially the face and hands. The action of these heat detectors does not, of course, depend in any way upon the presence of any visible rays (light). They work upon invisible radiation which our eyes cannot detect and which is always being radiated by all bodies whether we can see them or not.

Detection by Radio-micrometers

In the foregoing instruments the heat-sensitive elements were connected by wires to the galvanometer whose indications recorded the variations in the amount of heat falling on the element. It is possible, however, when we are using a thermo-junction as the sensitive element, to combine the element and the galvanometer in one unit. This is done by attaching the thermo-junction directly to the coil of the galvanometer so that it moves with, and sends the current it generates through, the coil. This combination of thermo-junction and galvanometer is known as a radio-micrometer and it is an exceedingly sensitive detector of heat.

Detection by Radiometers

With one exception all the more sensitive instruments for heat detection depend upon the use of delicate galvanometers. The exception is known as a radiometer and it consists of a small chamber, from which most of the air has been removed, containing a pair of light vanes suspended by an exceedingly fine quartz thread. One face of each vane is blackened and the vanes are attached to each other and to the supporting thread by little wisps of spun glass. These pieces of glass are easily able to bear the strain which is put upon them, for the total weight of the

vanes is well under 1/4000th of an ounce. Owing to the fineness of the quartz thread the vanes will move whenever there is the least pressure upon either of them, and, in particular, they will tend to twist about the vertical suspending thread if the pressure on one of the vanes exceeds that on the other. The movements of the vanes are made visible in the usual way—that is, by attaching to the movable system a minute mirror which reflects a beam of light and so indicates the smallest motion of the vanes.

When light or infra-red rays enter the case of this instrument they are allowed to fall on one of the vanes and not on the other. The result of this is a movement of the vanes and of the mirror. By measuring the displacement of the light-spot reflected from the mirror we can calculate the amount of radiation falling on the vanes.

It may seem curious, after our insistence upon the non-materiality of the electromagnetic rays, that they are able to produce a movement of anything material; in point of fact, however, the movement of the vanes of the radiometer or of those small light-mills which used so frequently to be seen in the windows of opticians' shops, can be explained by the action of the gas molecules which remain in the glass container.* Any one who has looked carefully at a small light-mill spinning in the Sun will remember that one surface of each vane was blackened while the other was polished. The result of this is that, owing to its greater absorptive power, the black surface gets warmer than the polished one. Any gas molecule which happens to hit the black surface will therefore rebound with a greater velocity than one which hits the cooler polished surface, and there is, in consequence, a larger pressure on the

* It must not be assumed, however, that light exerts no direct pressure on a metal surface.

black faces than on the polished ones. This explains why the light-mill spins, and why the radiometer vanes are moved by the action of the incoming light.

The Efficiency of Infra-red Detectors

The efficiency, as detectors of heat, of the instruments we have just described, depends greatly upon fine workmanship. The amounts of metal used in making thermojunctions and bolometer strips must be cut down to the smallest possible limit, so that a maximum percentage of the heat rays which are absorbed may be turned into something we can measure. The sensitiveness of heat detectors is often expressed as the minimum amount of energy to which they will respond, but it is interesting to compare their powers of detection with those of the most perfect energy detectors known to us, viz. the human eye and ear. Boyle, in his *Disquisition about the Final Causes of Natural Things*,* referred to the eye as being 'as exquisitely fitted to be an organ of Sight, as the best Artificer in the world could have fram'd a little Engine, purposely and mainly design'd for the use of seeing . . .' and we find no cause to modify his statement even after examining the sensitiveness of the most delicate 'little engines' we can now produce. The eye is wonderfully sensitive to light and it has been shown by measurement that it can detect an amount of energy corresponding to about 10^{-19} of that contained in the light of a candle or small electric pocket lamp. The ear is also an exceptionally delicate piece of apparatus—especially when one remembers that it has to respond to a greater range of 'notes' than the eye—but it requires about ten times as much energy as the eye to stimulate it. Some of the most perfect heat detectors will

* Published in London, 1688.

give indications of the heat of a candle over fifty miles away under suitable conditions.* One is astonished at the marvellous ingenuity and skill which have been used in fashioning such delicate instruments, but, by comparison with the eye and ear, they are crude and are affected only by many millions of times the energy required to produce the sensations of light and sound.

However crude, cumbersome, and complicated these artificial detectors of heat appear when compared with the eye and ear, it must be admitted that they are wonderful things. The reader who regards them as tiresome and trivial 'gadgets' may forget the details of their construction and remember only that they act as very sensitive thermometers or as artificial 'eyes' with which we may detect invisible rays whose existence would, without their aid, escape our knowledge. In the artificial arrangement the heat-sensitive cell replaces the eye; the wires which carry the electric currents from the cell to the galvanometer play the part of the nerves which lead from the eye to the brain; and the galvanometer acts as a brain to receive the stimuli which come from the sensitive cell.

Detection by Phosphorescent Substances

A further method of detecting heat rays depends upon their power of extinguishing the phosphorescence of certain substances. By phosphorescence we mean that property by which some things appear to store up light and give it out slowly when they are in the dark.

Phosphorescence is of great scientific interest, and the early records of the learned societies show that it received much attention about the middle of the seventeenth

* Since the flame temperature of a candle is low much more energy is emitted as heat than as light.

century, soon after the discovery of the so-called 'Bolonian' or 'Bolognian' Stone. This Stone is a mineral which occurs naturally in some parts of the world and particularly in the neighbourhood of Bologna. Its curious power of shining in the dark was brought to light through the activities of an Italian shoemaker named Vincenzo Casciarolo, who was, it appears, led to examine the Stone under the impression that such a unique substance must at least be the long-sought Philosophers' Stone. The connexion may not seem clear to us now, but we know that the alchemists identified Gold with Sol and that the Sun and Gold have for ages been common symbols of permanence. Since the Sun obviously had a great deal to do with the glowing of the Bolognian Stone, it is not unreasonable to surmise that the shoemaker believed that, through the Stone, he might be able to draw down from the heavens some of that quintessence by which to cure the defects of common metals and thus achieve the perfect Gold.

The early history of the Bolognian Stone is given in a curious little book published in Rome in 1680 by Marc' Antonio Cellio, and entitled *Il Fosforo, o' vero la pietra Bolognese, preparata per rilucere frà l'ombra*. A considerable portion of the book is taken up by an account of the way to prepare luminous paints from the Stone and of the use of painted images to play the part of wraiths, which, according to tradition, gleam with a pale unnatural light.

Phosphorescent substances are now commonly used in luminous watches, and, although we cannot be too confident of the way in which phosphorescence is brought about, we can form a general idea of what happens. It has recently been found that pure substances are generally unable to phosphoresce and that extremely small amounts of an impurity (often Zinc or Copper) have to be added to

the so-called 'active' compounds before they will behave as we wish. The impurity is distributed throughout the phosphorescent substance and makes active centres in it. When light falls upon the material it is absorbed and electrons are driven from the active centres. They come to rest temporarily at some distance from their proper homes, and wait until they are allowed to return. When their turn comes to go back they emit as light some of the light energy they had previously absorbed. They return gradually and not all at once, so that we observe a gradual decay in the amount of light which is given out by a phosphorescent substance, owing to the steady decrease in the number of electrons which remain away from their homes.

The phosphorescence of most modern luminous watch dials is *not* due to the previous absorption of light. The active substance is Zinc sulphide in which a small quantity of a radio-active compound has been incorporated. The Alpha-particles thrown out by the nuclei of the radio-active material crash into the active centres of the phosphorescent substance and, somehow or other, drive out electrons which emit light as they move back from one more or less stable position or orbit to another. The radio-active material takes the place of light in supplying energy to the phosphorescent compound, and the process of light emission may be likened to that which was described in the last chapter, where the production of light by glowing Hydrogen was discussed. This description of the machinery inside the luminous paint of one's wrist watch may sound fantastic, but if any one doubts the truth of the image, let him take a small magnifying glass and look steadily at one of the figures of his watch. He will see, not a uniform illumination of the figure, but a series of

bright scintillations appearing at intervals, and apparently at random, over the surface. The whole scene reminds one of a firework display in which many brilliant stars light up irregularly against the dark background of the sky.

These phosphorescent substances which store up light are not like radio-active materials, for we can easily alter the rate at which the light comes out. There is a phosphorescent composition known as Balmain's paint, which is a white powder containing Barium sulphide.* This glows brightly in the dark with a bluish colour after it has been exposed to ultra-violet light or to the light of the Sun or an electric lamp—it is giving up slowly what it had absorbed. We can hasten the rate at which the absorbed energy is surrendered by heating the powder. If we take a pinch of the powder from the light into a dark room and drop it on a hot plate it flashes up suddenly and brilliantly and is then dead. Whereas it would have continued to glow for some time if it had not been heated, nearly all the absorbed light is returned in a burst when it is warmed suddenly. This ability to store up light energy is not confined to substances which we normally regard as phosphorescent. Fused quartz, for instance, which has been exposed for some time to ultra-violet light gives a brilliant green light when it is strongly heated. The theory of this effect is obscure, but, for want of a better explanation, we may imagine that the electrons which had been displaced from their normal positions by the absorption of light are displaced still further by the heat, and that, when they have acquired this additional heat energy, they reach a stage at which their desire to return nearer to their homes is so strong that none of them can

* Pure Barium is a silver-like metal which is slightly harder than Lead. It does not occur naturally in the free state and was first prepared in 1808.

wait—they all rush back and give up energy in the form of light as they do so.

This effect is the basis of one of the most interesting methods of detecting infra-red rays. A beam of invisible rays falling upon a phosphorescent substance, such as Balmain's paint, extinguishes the phosphorescence suddenly. The way the phenomenon is used in practice is described in the next chapter. Another example of the antagonistic effects of infra-red and ultra-violet rays is shown by an experiment with Phosphorus. Phosphorus gives off clouds of white vapours when it is placed in a beam of infra-red rays, but these clouds are stopped immediately a beam of ultra-violet light is turned on. Yet another ingenious method of detecting infra-red rays of great wave-lengths has recently been described in scientific papers. This method has been developed in Germany, and it depends upon the concentration of the rays upon the surface of a membrane covered with a very thin layer of an easily evaporated solid. When infra-red rays fall upon the surface of the membrane, the solid evaporates and the coating becomes thinner. Results can be obtained with rays which will not affect even a specially sensitized photographic plate.

V

USES OF INFRA-RED RAYS

Detection of invisible objects. Secret signalling. Burglar alarms and warning systems. Fog penetration and 'seeing through fog'. Distant control of torpedoes and aircraft. Self-steering torpedoes. Photography of invisible objects through fog. Navigation and infra-red rays. Absorption of light and infra-red rays by fog and mist. Radiation and climate. Medical uses.

Detection of Invisible Objects at Night

WHILE the advances of science have made possible the development of closely packed centres of population and the provision of comforts on a scale which would otherwise have been out of the question, science at the same time puts into our hands more and more perfect weapons for the destruction of life and civilization. It may be said that all countries which have military responsibilities are watching the output of the laboratories of the world with the object of seizing upon any new idea or discovery which may have an application in warfare, and it is therefore not surprising that many proposals for the use of infra-red rays in land or sea operations have been examined.

We shall consider first of all the uses of infra-red rays for detecting invisible objects at night, when ships, aircraft, or men can move with a smaller chance of being detected by opposing forces. In the day-time we see things by virtue of the light of the Sun which comes to our eyes after being reflected from the surfaces of the object, but on a dark night we can only see things which are themselves luminous or which we illuminate artificially by such things as searchlights and star shells.

While the temperature of the objects which we wish to see is ordinarily not high enough to make them visible,

there are some which are sufficiently hot to be sources of appreciable quantities of energy of wave-lengths which are invisible. As we have seen, all hot bodies radiate infra-red rays and we can therefore say that there is a possibility of detecting the presence of invisible heated objects by using, instead of our eyes, one of the many methods of detecting infra-red rays.

This leads us directly to the conclusion that the detection of aircraft and vessels might be feasible because the engines of aircraft and the funnels of ships are hot and therefore radiate infra-red rays. By the same reasoning one might suggest that it would be possible to detect human beings in the dark because our bodies are normally at a temperature which is higher than that of our surroundings. The practicability of any of these schemes depends partly upon the quantity of heat which is emitted as infra-red radiation by the object we wish to detect and on the sensitiveness of our detecting arrangements.

Let us examine the difficulties which are encountered in endeavouring to locate aircraft flying on a dark night towards a large town or defended position. The machines fly at great speed and, in addition to a lack of knowledge of what point they may be over at any instant, we have no information about their height except that which is derived from a general knowledge of the habits of aircraft pilots. The difficulty of fixing the position of aircraft in the air and of following their course is thus immeasurably greater than the corresponding problem of locating and tracking a ship on the surface of the sea.

It is well known to those familiar with anti-aircraft work that efforts have been made to replace the eyes by the ears, and many different types of apparatus for locating aircraft depend upon the ability of the ears to give an idea of

the direction from which the sound of the aeroplane propellers is coming. It will easily be appreciated that this method of locating aircraft has distinct limitations, especially when it is remembered that, apart from unavoidable inaccuracies in the locating instruments themselves, the atmosphere often plays strange tricks with sounds; they may occasionally appear to be coming from a direction which is markedly different from that of the real source of sound, and it would clearly be useless to use such erroneous information for directing gunfire. It is also to be noted that this acoustic method of detecting aircraft would fail if the propelling machinery were made noiseless.

The problem of range-finding against aircraft is sufficiently difficult by day. It is even more difficult at night, and we need not marvel that all possible ways of improving the powers of defending forces have been examined and that the use of infra-red radiation was one of the methods singled out for thorough test. In America one set of trials was conducted with a receiving apparatus consisting of a 24-inch mirror which could be turned and elevated so that its axis could be made to point in any direction. At the focus of the mirror were placed a number of thermo-junctions and the electric current from these was led to a sensitive galvanometer. Some of the heat from a hot body placed on the axis of a mirror will be concentrated at the focus of the mirror just as light is concentrated at the focus of a burning glass, and an indication of this heat can be obtained by putting a thermo-junction at the focus. No indication—or only a very small one—would be given by a hot body which is not at some position on the axis of the mirror, so that we know that a hot body is somewhere on the axis of the mirror if the galvanometer shows that a current is coming from the thermo-junction.

In experiments made in the United States in 1919 a 150 h.p. aeroplane flew at a height of about 3,500 feet on a dark and hazy night and the distance of the machine from the infra-red detector varied between 4,000 feet and well over one mile. Clear indications of the direction of the machine were obtained in these trials although the engine was only running at about one-third of its full power, and the amount of heat radiated was consequently smaller than it would have been at full power. At a first glance it would seem that the method is full of hope, but we must not forget that there are other factors to be taken into consideration. Suppose that the sky is clear but that there are occasional patches of cloud or mist. When the mirror is pointing at the sky no heat will be coming into the receiver, but the passage of a cloud which obscures the sky will give an indication which may easily be bigger than that due to an aeroplane. The reason is that the cloud behaves as a warm body compared with the clear sky, and we can gain nothing by increasing the sensitiveness of our infra-red detector unless we can learn to discriminate between clouds and aircraft. It is also obvious that, supposing we were able to make a satisfactory receiver which would do all we wish, the answer of the enemy would be to screen their engines so that the heat would not reach the receiver, and we should be left to detect nothing but his shadow against the sky. For these reasons we must not be too optimistic about the value of infra-red rays as an adjunct to existing methods of defence against aircraft.

The detection of vessels at night by the radiation from the funnels is in some ways an easier problem than the detection of aircraft. We have a larger source of heat and a less rapidly moving target, but we have again to contend with difficulties introduced by the presence of clouds

or other bodies which can produce spurious indications. Under favourable conditions invisible vessels have been detected at ranges up to 6 miles with instruments similar, in all essentials, to those we have just described, but no one has yet shown how to make certain that the object causing the indication is indeed a ship.

It is also conceivable that infra-red ray detectors might be used for indicating movements of men at night in land warfare or the presence of icebergs at sea. There is no doubt that these things could be done if the difficulties mentioned above were overcome. In an experiment which was conducted a few years ago in France it was found that a man's head, appearing over the edge of the parapet of a trench, could be detected 50 yards away although it was naturally quite invisible in the dark at that distance.

Disasters at sea such as the loss of the *Titanic* with nearly 1,500 lives, and repeated delays due to the danger of collisions with icebergs which float across the lanes of ocean traffic, particularly in the North Atlantic, are costly reminders of the gravity of the perils of ice. A reliable method of obtaining adequate warning of the proximity of an iceberg would be a boon whose value it would be difficult to over-estimate, but up to the present none of the solutions which have been proposed has been found to satisfy the requirements of navigators. Experiments have, however, been made to test the value of infra-red detectors for this purpose, and a special receiver consisting of a gilded mirror with a heat sensitive element fitted at its focus was employed. The mirror was mounted on bearings and controlled by a pendulum so that it was unaffected by the rolling of the vessel and always remained pointing towards the horizon. The current from the sensitive

element was led to a special form of galvanometer which was also immune from the effects of the movements of the vessel in which the apparatus was installed. The difficulties which have to be overcome in using instruments of the necessary delicacy at sea are enormous, but, in spite of them, it was found possible to detect the presence of icebergs which crossed the axis of the mirror at distances of about 6 miles. This distance is naturally affected by the size of the iceberg and is smaller when the weather is foggy or hazy, but there is still a hope that refinements of the method may yet prove an asset in waters where ice is a menace even to the largest vessels. The level of our hope falls, however, when we remember that the smaller bergs, which are most difficult to detect, are more dangerous to shipping than large ones.

Use of Infra-red Rays for Signalling

The next application of infra-red rays which we have to consider is their use as signals. Many systems of signalling are now so rapid and certain, and so immune from interference, that there would be little reason for examining further methods if the secrecy of the matter transmitted and the origin of the signals were never of importance.

It is notorious that no system of code messages which remains in use for a long time, or is much used, can be counted upon to remain immune to enemy efforts at cypher-breaking. All messages sent out in cypher by wireless stations are so much material for the enemy to work upon, and, incidentally, it is generally possible to ascertain the position of a wireless transmitting station by the use of direction-finding apparatus. A signalling system which could not be tapped and which could be

worked reliably over even comparatively short distances, without the danger of disclosing the position of the transmitting stations, would have some military value, and experiments on the use of infra-red rays have been made to discover what advantages they offer.

Systems of signalling based upon the interruption of a beam of light by a shutter worked by hand in accordance with the Morse code have for a long time been in use at sea. The source of light is often an electric lamp, but in countries where the Sun is strong and the atmosphere is clear, great distances are regularly covered by signals made by reflecting the light of the Sun towards the receiving station by means of a mirror. If light signals are used at night the messages may be read by people for whom they are not intended, and the position of the transmitter may also be disclosed. Infra-red rays have advantages over light and wireless for secret communication over short distances. Owing to their invisibility, the fact that signalling is going on cannot be detected except by special apparatus, and since the rays may be sent out in a narrow beam, like an invisible searchlight beam, detection is impossible except in the direction of the beam itself.

In experiments made in France with infra-red signals the transmitter was a searchlight projector, but the radiation sent out from it passed through a dark screen or filter which stopped all the visible light and only allowed the infra-red rays to pass through. The receiver was a small mirror at the focus of which was fitted a heat-sensitive element connected to a galvanometer whose movements indicated the reception of signals. When the projector was trained upon the receiver it was quite invisible, but signals could be received over distances up to about 10 miles, with the certainty that no one without the

necessary scientific instruments could ascertain that signals were being made or who was sending them.

Another series of experiments conducted in France is particularly interesting because the infra-red rays were made to give a direct visible indication of their arrival at the receiving station. The transmitter was, as usual, a searchlight fitted with a screen to remove visible light and the receiver depended upon the power of infra-red rays to distinguish the phosphorescence of Zinc sulphide. In the particular form of receiver used the Zinc sulphide was laid upon an endless belt which passed over rollers, driven by clockwork, so that a fresh surface of Zinc sulphide was continually being exposed to the infra-red signals which were admitted through an aperture in the receiver box so as to fall upon the band. Before passing in front of the aperture the Zinc sulphide was caused to phosphoresce brightly by being exposed to the violet rays coming from a small electric lamp placed inside the box. If no infra-red signals are being received the band continues to glow brightly after passing the aperture, but Morse signals made by the transmitting station extinguish the phosphorescence and leave long or short dark spaces on the glowing band, so that the signals may be read by the eye. The whole of the band passes again under the light of the electric lamp before a fresh exposure so that its phosphorescence is renewed and the Zinc sulphide is ready to receive fresh signals. Using this kind of receiver ranges of more than 20 miles have been covered by invisible infra-red signals.

In another ingenious method of receiving infra-red signals neither the movements of a galvanometer nor the direct visual indication by phosphorescence are used to record the dots and dashes, but the ear is used instead.

The beam of infra-red rays is passed through a rapidly rotating disk perforated by a series of holes or slots, and then upon a sensitive cell such as the Thalofide Cell. This cell is connected through an amplifier to a pair of telephones and one hears then a continuous note corresponding to the rate at which the infra-red beam is interrupted by the perforated disk. If the transmitted beam is interrupted according to the Morse code the receiver with the telephones hears a series of long and short musical signals which are exactly like those heard with a wireless set when one is receiving Morse code signals from a ship.

In America experiments have been made on similar lines, but the type of transmitter favoured was a telescope used, as it were, the wrong way round. A low-power electric lamp, fitted in the telescope, projected a parallel beam of energy, from which visible light had been removed by a filter, towards the receiver and it was more efficient than mirrors for making a concentrated beam. The invisible signals could be received nearly 20 miles away, and the advantages of the infra-red rays from the point of view of spies who might wish to transmit intelligence from the shore to friends afloat, or across the enemy lines in land warfare, are obvious.

Telephoning by Infra-red Rays

In the foregoing paragraphs dealing with infra-red signalling we have confined ourselves to systems using the Morse code, in which the beam is cut off periodically by the operation of a tapping key which works a shutter in front of the source of the rays. There is, however, no reason why the infra-red beam should not be used to convey speech directly from place to place, and, difficult though this may appear, the arrangements for doing it are

simple in the extreme. At the transmitting end we require to alter the intensity of the infra-red beam in accordance with the fluctuations in the intensity of the sounds we produce in speaking. These sounds may be transformed into variations in an electric current by speaking into a telephone, and the resulting current may then be applied directly to the current flowing in an electric arc, if we happen to be using an arc as a source of infra-red rays. The additional current variations imposed upon the arc current will increase or decrease the amount of infra-red energy emitted by the arc in exact agreement with the fluctuations of the sounds of the voice which is speaking into the telephone, and these fluctuations will travel along the beam with the speed of light until they reach the receiver. Now the changes produced in the receiver depend upon the intensity of the radiation falling upon it, and these changes will therefore follow the fluctuations of the voice and may be transformed into sound by placing the sensitive element in the circuit of a telephone receiver and amplifier. There are other ways of achieving the same effect which could be developed if a demand for this method of telephony arose, and it may be of interest to notice that similar systems of telephony, using visible light instead of infra-red rays, have proved successful over considerable distances, while infra-red telephony has been carried on over ranges of several hundred yards.*

In considering systems of signalling by infra-red rays there are one or two points which do not leap to the mind as quickly as they should, owing to the tendency to forget that one is dealing with radiation which is totally invisible. Suppose one has an infra-red projector and wishes to com-

* A report that infra-red telephony has been effected in Italy at ranges of over 5 miles has just come to my notice. (J. B., Oct. 1929.)

municate at night with a person using the invisible beam. The beam must point directly at the person or he cannot receive the messages, and one cannot tell in the ordinary way whether the projector is in the right direction or not, because the beam does not show where it strikes. Without any additional arrangement the receiver will receive nothing except by chance. This little difficulty may be surmounted by using a most ingenious arrangement of mirrors which reflect the infra-red beam, not at any angle as does an ordinary mirror, but always exactly backwards along the original course of the incoming rays. If a beam of any kind of light or infra-red rays from a projector falls on this arrangement of mirrors the reflected rays come back to the projector. The person who wishes to send a message will be certain that his beam is pointing in the right direction if the receiver is fitted with these mirrors and the reflected beam comes back to the projector.

Burglar-alarms and Warning Systems

It has recently been stated in the press that infra-red rays were being used for burglar-alarms, and that invisible and unavoidable barriers might be made to take the place of watchmen and the ordinary electric systems which are employed in shops and warehouses. With the knowledge we have of the properties of infra-red rays it is easy to see how this may be done. Suppose we surround the place we wish to protect by beams of infra-red rays which are sent from projectors fitted into the panelling of a room so that the rays come through an infra-red filter and fall upon a receiver built into the opposite side of the room. Then any interruption of the beam will alter the electric current which flows through the receiver, and this change can easily be made to close a switch and set bells ringing or

start any other kind of alarm. The presence of the beam will be undetectable and it may be anywhere, so that an unauthorized person could not by any stratagem avoid giving the alarm if he ventured to cross the invisible beam. Nor could he tamper with the transmitter or receiver, because, if he did so, the alarm would immediately work.

The same principle could be applied to the automatic counting of people going through turnstiles or visiting museums, &c. There is nothing mysterious about it, and, in point of fact, it was proposed some years ago thus to obtain a warning if enemy vessels attempted to force a passage up a channel by night or in a fog. The infra-red projector and receiver would be placed on opposite sides of the channel, not too high above the water-level, so that it would be impossible for surface craft to pass through without breaking the beam, thus cutting off the rays from the receiver and giving the alarm. In actual practical trials of the infra-red method of barring a channel to the unexpected entry of enemy vessels, the width of the passage to be protected was about 5 miles. The receiver was fitted with the phosphorescent detector upon which fell the invisible beam of the projector on the other side of the channel. The moving band showed, of course, a continuous black line because the phosphorescence was extinguished by the rays from the projector, but, as soon as the rays were cut off by the passage of an invisible vessel along the channel, a bright spot appeared and it was known that a ship had passed. On one occasion a torpedo-boat steaming without lights in complete darkness was detected six times in succession as she crossed the invisible barrier. The only special merits of the infra-red rays for this purpose are their invisibility, which makes it possible that the enemy vessel might be unaware of the fact that they

had given their position away, and their power of penetrating through fog or mist under certain conditions.

Fog Penetration and 'Seeing through Fog'

The next possible use of the invisible rays is of more problematical usefulness than any of the foregoing, because it depends upon the ability of the rays to travel great distances in foggy or misty atmospheres. If we project a searchlight beam upon an object the light which is reflected shows us its details, but searchlight beams will not travel well through fog and, in addition, the eyes of people near the searchlight are blinded by the light which is thrown back by the fog particles in the beam, thus making vision doubly difficult. The same trouble is experienced by motorists in a fog when they are blinded by their own headlights. Orange-coloured front-glasses are a help under these conditions, because the shorter wave-lengths in the light are eliminated by the tinted glass and only the longer ones are transmitted. It is obvious that the range of a source of light cannot be increased by any arrangement of filters, because the filter cannot produce rays which were not originally present in the total radiation of the source, but a smaller proportion of the longer waves is reflected by the fog particles and the eyes are therefore less liable to be dazzled. There is thus a gain of visibility in spite of the loss of light.

If we went one step farther and put in an infra-red filter instead of an orange one the percentage transmission of the rays would be even better, but we should be worse off because we should see nothing whatever. We can, however, easily see how it would be possible to use the reflected infra-red rays and make them show us what was in front of us in a fog, and this will now be explained.

A newspaper picture when looked at under a magnifying glass is seen to be made up of very numerous small black and white dots or squares. In the dark parts of the picture there is a preponderance of black in the squares and the brain receives an impression of something uniformly dark. If we wished to send a friend a long way off a copy of the picture we could of course go and buy one and post it to him, but we will suppose we have to do it over a telephone wire. Taking the top row of small squares we might number them A1, A2, A3—up to A1000, and the second row B1, B2, B3—up to B1000, and so on for all the rows. Suppose the recipient has a piece of paper covered with small blank squares similarly numbered, then he could reproduce the original picture over the telephone if we merely telephoned the number of each square in turn and said if it was a black or white one. This way of telephoning a picture is not recommended, because even an ordinary newspaper picture contains a very large number of black and white spaces. The picture in *The Times* of 14 February 1929 of the scene in the Council Hall of the Palace of the Lateran in Rome, taken during the ceremony at which the Treaty between the Vatican and the Italian Government was signed, contained roughly one and a half million black and white dots.

If the picture were in the form of a negative we might flash a beam of light along the top row of squares and record the fluctuations in the beam with a light sensitive cell placed on the other side of the negative. An electric current flowing through the cell would change rapidly according as the beam was stopped or allowed to pass by a black or white square. The travelling beam of light can be made to cover the whole of the negative by using a rotating disk perforated with a series of holes arranged in

a spiral so that the beam of light traces a path over all the rows of squares in turn and produces corresponding variations in the electric current through the cell. This rotating disk or its equivalent is an essential portion of most of the so-called 'Television' systems, and it is interesting to note that it dates from 1884. We have heard so much recently about Television that we are apt to forget that no portion of the apparatus used is novel to scientists, and that the principles upon which successful Television depend have been known and understood for a comparatively long time. The advances which have been made lately are the result of the application of improved scientific apparatus—for instance, the wireless valve and special light-sensitive cells—to old systems.

The varying electric current from the cell may be transmitted to the receiving station and made to work a flashing lamp so that it will glow brightly when the beam at the transmitting station shines through a 'hole' in the negative and go out when the beam falls on a dark square. All we now have to do is to distribute the flashes of the receiving lamp over a screen so that when the transmitter is dealing with the white square L 371, then the light at the receiving end is shining on its square L 371. If the complete process of scanning the negative is completed sixteen or more times per second the mind does not realize that the receiving screen is not continuously illuminated and will accept the impression of a complete picture which is given to it by the rapidly moving spot of light.

It is obvious that a similar system could in theory be applied to the scanning of distant invisible objects by an invisible moving spot. The reflected infra-red rays would be received with an infra-red sensitive cell, transformed into light, and redistributed upon a screen just as in simple

Television with ordinary light. There is nothing impossible about seeing at a distance in the dark, or through fog, by infra-red rays, but these things will certainly not be useful until practical Television is an accomplished fact, which it is at present far from being. By that time we shall probably have more definite information about the distances that infra-red rays will go through different kinds of fog and mist and be able to say whether or not satisfactory ranges could be attained. So far as military applications are concerned the danger of relying upon the secrecy of a piece of apparatus, of which the enemy may know as much as one does oneself, must not be overlooked, and this consideration places many otherwise promising schemes at a discount.

Distant Control of Torpedoes and Aircraft

In warfare it is often desirable to have the power of directing an offensive weapon such as a torpedo or an unmanned aeroplane after it has been loosed against the enemy, and much has been written about the control of torpedoes and aircraft by wireless from a base. Torpedoes and aircraft have been steered by wireless impulses, and we may anticipate that this mode of attack from a distance will be further developed. The receiving arrangements in a controlled torpedo or aeroplane are necessarily complicated because many operations, which could easily be carried out by a man on the spot, are not so simply effected from a distance when orders have to be transmitted by signal and translated into action by electrical apparatus fitted in the controlled craft. But when one remembers the uncanny precision with which an automatic telephone exchange selector finds, without human aid, a number which the subscriber indicates merely by turning a dial

so many times through certain distances, it is easy to realize that the movements necessary to control a torpedo can be carried out although the torpedo may be miles away from the control officer.

One of the difficulties which have to be overcome in the distant control of machines by wireless is the possibility of jamming the control signals by enemy signals of the same wave-length. This difficulty is not insuperable, but in the infra-red rays we have an alternative which cannot be jammed if certain precautions are taken. The most obvious way of reducing the possibility of enemy interference with the control signals is to fit the torpedo or controlled craft with a receiving element which is screened from impulses received from any direction other than that of the controlling station. To do this we need to mount the receiver on a turntable which is automatically maintained so that the receiver points towards the controlling station no matter how the controlled craft moves. We have, in the gyroscope, an instrument which may be arranged to keep its axle pointing in a fixed direction in space independently of the movements of the body in which it is mounted, and so it is possible to stabilize the direction of a receiver of infra-red rays so that it does not alter appreciably when the controlled craft turns. The torpedo, being fitted with an arrangement of mirrors* for showing the control officer when his beam is pointed at the receiver, can be kept in the beam along which signals may be sent just as they are sent to an automatic telephone exchange by a subscriber. Instead of finding a number, however, the signals received in the torpedo may be made to alter its speed and course so that it will hit its target.

In case these remarks on the distant control of moving

* See page 118.

craft may seem visionary, it is relevant to point out that, remembering the fundamental relationship between light and infra-red rays, there is no difference in principle between controlling a vessel by infra-red rays and controlling it by light, and that the movements of vessels have, in point of fact, been controlled by light. The experiments to which we refer took place in the early stages of the War (1915–16) and were largely due to the interest of the late Lord Fisher. The installation was by no means an elaborate one, but, in spite of this, the little boat in which the light-sensitive elements were fitted could be made to stop or start, turn to port or starboard, or fire a small gun, purely by flashing upon the receiver the beam of an ordinary naval searchlight. This apparatus was first tested afloat on Penn Pond, Richmond Park, but it afterwards worked successfully at sea at ranges up to 5 miles.

Self-controlled Target-seeking Torpedoes

A further advance on these controlled craft is theoretically possible. This is to fit into the torpedo or aeroplane, apparatus which will make it automatically target-seeking —or, in other words, once it is loosed in the general direction of the target it corrects by itself any inaccuracy in the original aim or any error due to an alteration in the position of the target during the time taken by the self-controlled weapon to cover the distance between it and the target. This may sound too much like magic to be true, but it is a fact that we have complete knowledge of the principles on which it could be done. The difficulties which would have to be overcome in building a practical weapon lie mainly on the instrumental side; we need, for instance, receivers of great sensitiveness and controlling

devices of very rapid action, and these are things which come gradually with increasing perfection of workmanship and experience with existing instruments. At present self-controlled machines are more suitable for music-hall demonstrations than for warfare.

In order to understand how a torpedo might be made target-seeking we must remember that the funnels of a vessel are hot and radiate infra-red rays in every direction. If we had a small box fitted with a lens so that the image of distant objects was focused upon a plate as it is in a camera, the image of a ship could be made to fall in the centre of the plate when the centre line of the box was in line with the direction of the ship. Now suppose the plate in the box is divided into three vertical strips, a narrow central one with two broader ones on each side, and suppose that these strips are made of some substance which is sensitive to heat rays—Thallium sulphide, for instance. Then the direction in which the box is pointing decides which strip the image of the vessel will fall upon; that is, the central strip will be heated by the rays coming from the ship's funnels if the box is pointing directly at the vessel and the right or left side strips will be heated if the box points to right or left of the target. If the box is fitted to a torpedo the three strips can be connected to electrical instruments in this way. If the heat falls upon the central strip (i.e. the torpedo is pointing at the enemy) the torpedo engines are made to go full speed ahead. If the heat falls on the left-hand strip it means that the torpedo is pointing to the left of its target and this strip can be made to control an electric motor which moves the rudders so as to bring the hot spot back upon the middle segment of the receiver box. Thus the heat rays will always act upon the sensitive segments of the receiver box so that they automatically

correct the course of the torpedo and keep it pointing in the direction of the target. We must not imagine that a perfect torpedo working in this way could be produced to-morrow, but it is certain that we could make at any time a model which would work in the laboratory as described, and there was in existence before the war a scientific toy known as the 'Electric Dog' which followed a small light and was controlled in a similar way by the visible radiation from the lamp. It always propelled itself towards the source of light, just as a moth flutters towards a candle.

Photography of Invisible Objects by Infra-red Rays

Since the eye is sensitive to a restricted band of wavelengths it is clear that the limit of visibility of a light is determined by the absorption of visible light by the atmosphere. A source of light becomes invisible when the intensity of the original energy is so attenuated by the effects of distance and absorption that it falls below the point at which the eye will respond. In some circumstances, however, infra-red rays will penetrate an atmosphere which is opaque to ordinary light, and we may make use of this effect to take photographs of objects which are not revealed by the eye or by an untreated photographic plate. If, as was suggested in Chapter IV, we add certain dyestuffs to ordinary commercial photographic plates we can make them sensitive to infra-red rays which are invisible to the eye and which would not be revealed by an unsensitized plate. Using this method photographs have been taken, at great distances, of objects which no eye, aided or unaided, could ever detect. These sensitized plates have been used for photographing the surface of Mars, which is normally obscured by a cloudy atmosphere

opaque to visible radiation; they may also be valuable in the cinema industry because 'night photographs' can be taken in daylight. Since the sky is cooler than most objects the sky would appear dark and the scene bright. Photographs taken at night by artificial light present this appearance.

Figs. 14 and 15 are reproductions of two photographs of the same distant scene taken from the top of Mount Hamilton. The Yosemite Valley, which is 120 miles away, is in the extreme distance and the town of St. Juan, 13 miles from Mount Hamilton, is in the intervening valley. No trace of St. Juan or of any of the other features of the distant landscape can be seen in Fig. 15, which is a reproduction of a photograph taken with an ordinary plate, but these and many other details stand out clearly in Fig. 14, which was taken with a specially sensitized plate. Fig. 13 is a photograph of Mars taken half on an ordinary and half on a special plate. The planet, which stands out clearly in one half, cannot be seen at all in the other.

In practically all the possible applications of infra-red rays we have so far considered the advantage of these rays over others has generally rested upon their invisibility or upon their power to penetrate atmospheres in which the visible rays are absorbed. It is not our purpose to discuss the former advantages, but the latter are of some scientific interest.

Penetration of Infra-red Rays; Factors which limit their Travel

We have seen that the absorption and emission of waves by *atoms* is due to the promotion or degradation of electrons in the orbits within the atom, and that a number of

Fig. 14. Photograph taken with a specially sensitized plate

Fig. 15. The same view taken on an ordinary plate

infra-red rays are produced by atoms in this way. The molecules of compounds are, however, held together by electrical attractions and it would be reasonable to expect that two atoms thus held together would behave, under varying electrical forces such as those due to light or infra-red rays, very much as a pair of weights connected by a spring would behave when acted upon by a variable mechanical force. The connected weights will absorb mechanical energy and attain a large vibration if the force is of the right frequency, and molecules will similarly absorb electrical energy if the frequency of the electrical forces happens to be just that to which the internal structure of the molecule will respond.

Now we notice in everyday life that large animals have slow and clumsy movements, while the smaller ones are brisker and more agile. Large organ pipes make low notes —the little ones, shrill and high pitched; the wings of a gnat beat fast and an eagle's wings are heavy and sluggish. On this analogy we might expect that, the seat of electrical vibrations of high frequency being within the atom, the slower vibrations might be found to arise from the movements of structures larger than the atom—i.e. from molecules. If this were so infra-red rays would be little absorbed by atoms themselves, a little more by simple molecules containing two atoms, and still more by complicated molecules, in which there are many atoms and therefore many ways in which the individual atoms can vibrate relative to each other.*

Experiment shows us that this picture is not very wide of the mark. Infra-red rays easily pass through pure dry

* Much information about the structure of *molecules* is being obtained by examining the absorbing power of substances in the infra-red region of the spectrum.

air, but when Carbon dioxide (CO_2) or water vapour are present a marked absorption occurs. This absorption of heat by molecules of gases containing many atoms is easily shown by exposing a thermo-couple to a source of heat, the radiation from which passes through a tube having glass ends. If the tube is first filled with Oxygen or air and is then refilled with Carbon dioxide or any more complicated gas such as marsh gas (CH_4), the galvanometer connected to the thermo-couple will immediately show that less heat is being transmitted.

In considering the transmission of electrical vibrations of wave-lengths corresponding to visible light and the infra-red rays through the atmosphere we have to examine another way in which the intensity of the rays is reduced. In the preceding paragraphs the energy of rays of certain wave-lengths was absorbed because the internal structure of the molecules of the air seized upon it and retained it, but there are, in the atmosphere, numbers of motes, specks of dust or very small drops of water (fog or mist), which are assemblies containing numerous molecules, and they are often as large as, and sometimes larger than, the wave-length of the longest visible rays. Large particles such as these interfere with the passage of short waves merely because of their size—one could not hope to see clearly through an atmosphere full of tennis balls, and the greater the number of the small particles in the fog the greater will be the absorption. Also we have to remember that the shorter wave-lengths are more impeded than the longer, so that, in an atmosphere containing a number of motes of a size comparable with that of the wave-length of the radiation which is being transmitted, the light which succeeds in getting through is generally richer in the longer wave-lengths than was the source. This explains,

of course, why it is that the light of the Sun just before sunset, and of a street-lamp seen through a fog, appear much redder than they are in reality.

The total effect of impurities in the atmosphere upon light which is transmitted through it is well shown by experiments with searchlights and lighthouse lamps. These lights are very intense and rich in short waves on account of the high temperature of the sources employed. Under some atmospheric conditions the light at a short distance will appear green and will change to amber, orange, and red as we go further away. It will be clear from this that the most intense source of light is not necessarily the best for penetrating the atmosphere under all conditions, and the predictions of theory were well borne out when the Germans replaced the 10,000 candle-power oil lamp in a lighthouse on the island of Heligoland by a 1,000,000 candle-power arc lamp. In foggy weather the more powerful light was visible over a far shorter range than the oil lamp, owing to the deficiency of the former in rays which were capable of penetrating fog. The reduction in the range of visibility of lights in misty weather is enormous. On clear days a 4,000 candle-power white light is visible about 20 miles away, but over 2½ million candle-power would be required to cover the same distance in a mist. The difference between the fog-penetrating powers of different coloured lights is easily seen if one looks through a fog at an illuminated sign containing red and blue lights. As the distance increases the blue lights are soon lost to sight, while the red ones are still plainly visible. This shows that the longer (red) waves have an advantage over the shorter (blue) ones.

If we had full information as to the sizes of the particles which actually occur in fogs and sea mists we should be

able to calculate how much of any particular kind of radiation would penetrate through them. But, as we have already noticed, some of the absorption of the atmosphere is due to the presence of water-vapour and Carbon-dioxide molecules, and we should therefore need to know the concentration of these gases before we could attempt to offer any reliable opinion as to the amount of energy that would pass through an ordinary sea fog, in which absorption is due partly to the stopping power of comparatively large collections of molecules and partly to the direct action of individual molecules.

It is unfortunate that fogs and mists differ greatly in the sizes of the particles they contain as well as in the number of particles in any given volume. An examination of the information which is available for sea fogs tells us that we should not expect too much from the infra-red rays. The size of the particles is usually much greater than the wave-length of the longest infra-red ray we can at the moment hope to use practically, so that, except under unusually favourable conditions, there will not necessarily be a great deal to choose between the infra-red and ordinary visible light from this point of view.

A more acute interest has been taken in fog-piercing lamps, beacons, and searchlights since aeroplanes became common and all the troubles of fog were encountered once again in an accentuated form. Attempts have been made to reduce the dangers of ground fogs by using beacons which are rich in light of the longer wave-lengths—i.e. the red end of the spectrum. At Lympne there is a 6,000 candle-power Neon lamp which is visible 45 miles away in clear weather. When there is a ground fog the lamp is itself invisible but the top of the fog bank is tinged with a reddish glow, showing that some of the red light has

been able to find its way by devious paths through the mass of fog particles. A proportion of the light from a sufficiently powerful arc lamp would of course penetrate a fog because white light contains some red rays. The red Neon lights are preferred only because they produce a greater percentage of red rays than the arc or other 'white' lights, and are therefore more economical.

We may say with confidence that infra-red rays would penetrate ground fogs even better than the red Neon light, but the great disadvantage is that the pilots would require special instruments for receiving the invisible rays, whereas they can see the red light without any artificial aid. Direct observations are always preferable to any others when safety of life is at stake and much more information is needed before scientists will be able to say that the problems of navigation in fog are solved. Investigations which may provide this knowledge are in progress in Germany, where the possibility of using infra-red rays for guiding aircraft in fog or when visibility is low is being examined. It is difficult and often dangerous to venture to predict what the future holds in store, but the author is inclined to think that the solution to the fog problem may be met by using waves which are longer than those commonly called infra-red and shorter than the shortest 'wireless' waves now in common use. We cannot at the moment either produce or detect efficiently waves of the length that seem to be needed. An early solution may be found of these problems; but we may, on the other hand, have to wait for some new fundamental theoretical discovery before our desire can be accomplished. The optimistic predictions which are frequently made in the lay press certainly rest on no solid foundation, and the writers, in their enthusiasm for some 'new' discovery, are apt to lose

sight of the limitations which Nature automatically sets on every application of science.

Infra-red Rays and Climate

From the consideration of the transmission of infra-red rays through the atmosphere we are led to ask what is the influence of these rays on the temperature of the earth. As we have seen, all bodies are continually losing and gaining energy and constancy of temperature is attained only when the rates of gain and loss of energy are equal. The temperature of the earth depends upon exactly the same laws as the temperature of any other body, but the relative importance of the different factors which determine its temperature are naturally most complicated and difficult to separate one from another. We know that the earth's temperature is subject to some form of natural regulation and that it can only fluctuate between certain extremes which, although they differ according to latitude and height, are roughly fixed. Not all the radiation coming from the Sun is able to penetrate the earth's atmosphere because certain wave-lengths—notably in the ultra-violet—are absorbed by gases in the atmosphere, but the remainder falls on the surface of the earth. Of this fraction some is directly reflected and some is retained by the earth and tends to raise its temperature. The earth radiates energy but, owing to its low temperature, all the re-radiation lies in the infra-red and much of this cannot escape beyond the atmosphere owing to absorption by gases such as Carbon dioxide, water vapour, and ozone, and the atmosphere thus acts as a covering blanket tending to maintain the heat of the earth. An accidental increase or decrease in, say, the proportion of Carbon dioxide in the atmosphere would alter the temperature of the earth so that it might

rise above the present level or there might be an increase in the area of the polar ice-caps. The reason for this is clear when we remember that the blanket of gas would still allow a large proportion of the total radiation of the Sun to pass through it; but a greater percentage of the outgoing radiation would be retained if the effective thickness of the blanket were increased by the addition of more Carbon dioxide to the atmosphere. Any other alteration in the composition of the blanket which favoured either incoming or outgoing radiation would similarly affect the earth's temperature, which would rise or fall accordingly. We are here admittedly in a field in which speculation flourishes and no one theory is yet capable of bearing the load of all the facts. To digress for a moment, let us consider what would be the most likely effect of filling the atmosphere with clouds of small dust particles. First of all there would be a noticeable decrease in the total amount of radiation reaching the surface of the earth, because the dust would stop some of it and send it back into space. The dust particles would, however, have a smaller stopping power on the energy which is re-radiated by the earth because it is of longer wave-length, so that, on the whole, the effect of the dust particles would be to lower the temperature of the earth. Let us now endeavour to put some sort of check on our theory. It is well known that vast amounts of dust are thrown into the atmosphere during volcanic eruptions. So great is the quantity of material ejected that it has occasionally been possible to trace the course of the dust over several circuits of the globe and, if there is any relation between our theory and the facts, we ought to be able to point to effects of volcanic dust on the weather. When we come to look at the records which are available we find facts which, to say the least of

it, suggest that there are strong reasons for attaching some importance to the theory. We find, for instance, that the cold years of 1783–4–5 followed the great explosion of Asama in 1783, and that 1816, the 'year without a summer' or 'eighteen hundred and froze to death', followed the eruption of Tomboro, in which 56,000 people lost their lives and which is said to have thrown up so much dust that there was darkness for three days at a distance of three hundred miles.

The examples we have chosen are among the more striking ones, but an examination of numbers of similar occasions on which severe winters have followed closely upon notable eruptions—and text-books on climatology contain many of them—shows that there is without doubt some connexion between the two sets of events. Their actual significance still lies hidden from us and we must be diffident about drawing any conclusions as to what are causes and what effects. It is conceivable that, since the periods at which sun-spots are at a maximum show a relation to the frequency of earthquakes, an increase or decrease in the radiation falling upon the earth may be associated with changes in the normal distribution of atmospheric pressure on the earth so that any weak places in the earth's crust are subjected to unusual stresses, thereby increasing the chance of seismic disturbances. Observation confirms that earthquakes are often accompanied by low local barometric pressure which, although it may appear a minor matter, actually involves colossal pressure deficiencies when the reduction affects a large area of the earth's surface.

It is not impossible that past glacial ages have been brought about by agencies similar to those to which we have just referred, and that the invisible infra-red rays are

always playing an important, if unappreciated and not fully understood, part in the stage-management of the small globe on which we live.

Use of Infra-red Rays in Medicine

Like the earth, the temperature of the human body is regulated by a complicated balance of heat exchanges. Heat is gained by the combustion of food within the body just as a boiler is heated by the combustion of fuel; the body acquires or loses heat also by contact with the atmosphere and by radiation.

The use of radiant energy in medical practice has increased remarkably during the last ten years, and special sources of light which are rich in ultra-violet rays are now in common use in many homes. The effects of rays of different wave-lengths upon the human body are closely related to the ability of the rays to penetrate the tissues, but the actual reason for the beneficial effects of radiation is by no means understood and there is little reliable information about the variation of the absorptive powers of different tissues for different wave-lengths. The superior penetration of the red rays* is easily demonstrated by holding one's hand in front of an electric lamp. The red colour which one sees is an indication that these rays penetrate the thickness of the hand more readily than other visible rays, but this is no criterion of what happens in the infra-red region. Thus we are fairly safe in assuming that the infra-red rays which are absorbed by water will not penetrate far into the body and will mainly produce heating of the surface.

One result of this ignorance is that generally no

* Red light was used in the ninth century in the treatment of small-pox.

definite choice of the most suitable wave-length for a particular treatment can be made, and treatment by radiant energy often implies exposure to all the waves (ultra-violet, visible, and infra-red) which are given out by the particular source chosen, in the hope that one or more groups of waves will have the desired effect. Reasoning on these lines, it is to be anticipated that treatment by radiant energy would affect Europeans and Negroes differently, for the pigment in the negro epidermis must certainly filter out some of the rays which would penetrate more deeply through the skin of a European.

Owing to their greater penetrative power, certain infra-red rays, which are not much longer than the visible red rays, are valuable in the treatment of lumbago, neuritis, neuralgia, rheumatism, &c., and the sources commonly used are electrically heated wire resistances, like those in electric fires, and carbon arc lamps which emit light as well as heat. When the visible light is harmful, as it may be when there is inflammation, filters made of glass containing oxides of Iron and Manganese are used to eliminate the visible light and the patient is exposed only to the infra-red rays.

Setting aside the therapeutic value of radiation, the understanding of the physiological effects of different rays is important because we must, in this climate, use artificial sources of heat in which the distribution of energy among the different waves differs from that of the natural source, namely the Sun. It is not sufficient merely to install any source of heat which is capable of keeping the air at a suitable temperature: it is possible that the source we choose will lack those waves which are important from the point of view of health, or it may produce others which are useless or even harmful. Artificial

sources of heat emitting a large proportion of energy in infra-red waves which are just invisible have been employed in warming enclosures in which certain warm-blooded captive animals are kept, and the good results which have been obtained may be due to the ability of these rays to penetrate the skin and warm the blood. Sources of heat like hot-water pipes, which are not rich in the required rays, are useless for this purpose, and it is possible that the reason for the dislike that many people feel for special forms of artificial heating are in reality due to a subconscious realization that, although the temperature may be right, the body is not receiving what it needs to keep it healthy and comfortable.

It is clear that a wide field for investigation is open to doctors, physicists, and bio-chemists, and we may hope that research will eventually show how rays affect us and make it possible to specify the use of rays for curing special conditions. It would at least be satisfactory if some of the great mass of information about infra-red rays which has been accumulating rapidly during the last ten years could be applied to some humane purpose.

APPENDIX I

Note on Electrons

When electrons were first discovered, and for many years afterwards, it was believed that their behaviour was best explained by assuming them to be small material particles carrying negative electric charges. The charges were determined experimentally by several different methods, and their apparent weight was deduced from the results of many careful measurements. As years passed by and the Rutherford-Bohr atomic model was formulated, the existing information about electrons and our elementary picture of them dovetailed admirably with the newer knowledge. A glance at the results of the calculations in Appendix II, even though the process be not understood, will probably convince even the most sceptical that there are strong reasons for believing in the physical existence of electrons. A more beautiful agreement between simple theory and complex Nature would be difficult to find, and we shall readily forgive the many whose reliance on the electron theory was so strong that it led them to believe that our ideal electrons were real entities.

By a strange coincidence the 'father of the electron', Sir J. J. Thomson, has a son who is now Professor of Natural Philosophy in the University of Aberdeen and was the first man in this country to demonstrate that an electron cannot be the simple concentrated charge we have assumed it to be. In certain experiments an electron behaves as if it were a train of waves—i.e. its properties are partly explainable by giving it the properties of a charged particle and partly those of a kind of wave motion or vibration. This is worth noticing, because we have seen in Chapter III that light, which we learnt to look upon as a wave-motion, has been shown to behave partly as if it were little particles. Light and electrons, which seemed a few years ago to be manifestations of entirely different forms of activity, now appear to have much more in common than we thought. In our resentment at the trick which Nature has played upon us we must not forget the extraordinarily valuable deductions which have been made on the basis of the old electron theory, nor should we minimize the importance of Thomson's conception of the electron.

To discuss the chances of a complete reconciliation between the

two views of electrons would lead us too deeply into the details of theories which are only now forming themselves. It is, however, interesting to notice that, in a recent paper on the electron, Sir J. J. Thomson retains the idea of a charged particle, but gives the particle a complicated internal structure so as to provide a means of producing waves, and he thus combines the particle image with a structure which is possibly capable of explaining some of the phenomena demonstrated by his son. Another prospect is that there is no such thing as an electron—that our 'solar system' atomic models bear no relation to reality, and that what we looked upon as material particles are nothing more tangible than *positions* at which there are peculiar relations between two sets of imaginary waves.

The main purpose of this note is to remove any idea that finality in Physical Theory is ever likely. By our processes of abstraction from the real we strip reality of almost every quality which makes it real. We are left with ghosts and we are apt to be surprised that they do not always behave as real things do. We are continually seeking some solid basis for understanding the world we perceive, clutching always at conceptions which vanish from our too material grasp and pursuing, like Burke's shadows, what seems fated to elude us. The idea is expressed in Pascal's *Pensées*—'Quelque terme où nous pensions nous attacher et nous affermir, il branle et nous quitte; et si nous le suivons, il échappe à nos prises, nous glisse et fuit d'une fuite éternelle.'

APPENDIX II

Derivation of the formula for the Balmer Series from the basic assumptions of Rutherford, Planck, and Bohr

The Hydrogen atom consists of a massive central nucleus with a charge $+e$. Around this nucleus an electron of mass M and charge $-e$ revolves in an orbit. Let the radius of a possible orbit be r_1 and let the corresponding velocity of the electron be v_1.

Then the electrical force of attraction between the nucleus and the electron keeps the electron in its orbit, and we have, accordingly, the relation:

$$\frac{e^2}{r_1^2} = \frac{Mv_1^2}{r_1}.$$

According to Bohr's Theory we have also:

$$Mv_1 r_1 = \frac{mh}{2\pi},$$ where h is Planck's constant and m is a whole number. From these two equations we deduce

$$r_1 = \frac{m^2h^2}{4\pi^2 Me^2} \text{ and } v_1 = \frac{mh}{2\pi Mr_1} = \frac{2\pi e^2}{mh}.$$

If we reckon the potential energy as zero when the electron is at an infinite distance from the nucleus, then the potential energy of the electron in an orbit at a distance r_1 from the nucleus is $-\frac{e^2}{r_1}$ and the total energy, kinetic and potential, of the system is

$$\frac{Mv_1^2}{2} - \frac{e^2}{r_1} = \frac{2\pi^2 e^4 M}{m^2h^2} - \frac{4\pi^2 e^4 M}{m^2h^2} = -\frac{2\pi^2 e^4 M}{m^2h^2}.$$

Similarly the total energy in any other orbit is $-\frac{2\pi^2 e^4 M}{n^2h^2}$,

where n is also a whole number. The difference between these two energies is equal to that emitted in a Quantum jump and is, according to Planck, equal to $h\nu$, where ν is the frequency of the emitted radiation. Thus:

$$h\nu = \frac{2\pi^2 e^4 M}{h^2}\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \text{ or } \nu = \frac{2\pi^2 e^4 M}{h^3}\left(\frac{1}{n^2} - \frac{1}{m^2}\right),$$

which is the formula given in the text. The numerical values of M,

e and h have been determined experimentally and their values are respectively 9×10^{-28}, $4 \cdot 77 \times 10^{-10}$, and $6 \cdot 55 \times 10^{-27}$ in metric units. The value of ν corresponding to the first line of the Balmer Series is thus approximately:

$$\frac{2 \times 3 \cdot 14^2 \times 9 \times 10^{-28} \times 4 \cdot 77^4 \times 10^{-40}}{6 \cdot 55^3 \times 10^{-81}} \left(\frac{1}{4} - \frac{1}{9}\right)$$

$$= 3 \cdot 27 \times 10^{15} \left(\frac{1}{4} - \frac{1}{9}\right) = 4 \cdot 5 \times 10^{14}.$$

The number of waves per centimetre corresponding to this line is equal to the frequency ν divided by the velocity of light in centimetres per second and is thus $\dfrac{4 \cdot 5 \times 10^{14}}{3 \times 10^{10}} = 15{,}000$ approximately. The figure given in the text, which was obtained by actual measurement, was 15,233·22.

Just as a matter of interest we shall calculate the radius of a Hydrogen atom. Taking the formula

$$r_1 = \frac{m^2 h^2}{4\pi^2 M e^2},$$

we put $m=1$, i.e. we assume that the electron is as near the nucleus as possible, and insert the appropriate values of π, h, e, and M. We obtain the answer $r_1 = 0 \cdot 54 \times 10^{-8}$ or the diameter is about 10^{-8} centimetres, which is very nearly the equivalent of the figure we were led to expect in Chapter II.

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